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FURTHER STUDIES OF TURBULENCE STRUCTURE
RESULTING FROM INTERACTIONS BETWEEN
EMBEDDED VORTICES AND WALL JETS
AT HIGH BLOWING RATIOS

by

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December 1989

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Interactions of wall jets and vortices embedded in turbulent layers commonly occur near gas turbine blades and endwalls where film cooling is employed. These interactions frequently result in undesirable heat transfer effects at blade and endwall surfaces. In this study, a crossed hot-wire probe is used to measure the turbulence structure resulting from this type of interaction.

The vortex is generated using a half delta-wing vortex generator mounted at 12 degrees with respect to a 10 m/s mean velocity flow over a flat plate. A single injection hole. 0.95 cm in diameter, inclined 30 degrees to the horizontal, is positioned 59.3 cm downstream of the vortex generator. The vortex generator is positioned so that vortex upwash or downwash could be located over the injection hole. Streamwise

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At low blowing ratios (m = 0.5 and 1.5) the vortex dominates the flow. Significant alterations to the turbulent structure are seen in the Reynolds stress components, vorticity distributions and mean velocities. At higher blowing ratios (m = 2.5 and 3.5) the jet dominates the flow, the vortex is blown away from the wall, and its turbulence effects are dispersed over a larger area.

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Further Studies of Turbulence Structure Resulting from Interactions Between Embedded Vortices and Wall Jets at High Blowing Ratios

by

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B.S.CEM, Oregon State University, 1980

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ABSTRACT

Interactions of wall jets and vortices embedded in turbulent layers commonly occur near gas turbine blades and endwalls where film cooling is employed. These interactions frequently result in undesirable heat transfer effects at blade and endwall surfaces. In this study, a crossed hot-wire probe is used to measure the turbulence structure resulting from this type of interaction.

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LIST OF SYMBOLS

SYMBOL	MEANING
B,K,n	hot-wire calibration constants
C	temperature drift correction factor
C_d	discharge coefficient
d	injection hole diameter
E	anemometer voltage
E_{corr}	anemometer voltage corrected for temperature drift
E_{oc}	no-flow voltage extrapolated from velocity calibration
$E_{o(measured)}$	measured no-flow voltage
m	blowing ratio
OHR	overheat ratio
T	turbulence intensity, temperature
T_∞	freestream temperature
T_{cal}	freestream temperature when hot-wire probe is calibrated
U_{eff}	effective cooling velocity
U_e, U_∞	local freestream, freestream velocity
U_{inj}	injectant velocity
U,V,W	instantaneous velocities in x,y and z directions respectively
$\bar{u},\bar{v},\bar{w}$	mean velocity components in x,y and z directions respectively
u',v',w'	fluctuating components in x,y and z directions respectively

v^*	friction velocity
$\vec{V}$	secondary flow vector
x	streamwise distance measured from boundary layer trip
x'	streamwise distance measured from downstream edge of injection hole
y	vertical distance
Ycen	vertical location of vortex center
Ycore	average vortex core radius in vertical direction
z	spanwise distance measured from centerline
Zcen	spanwise location of vortex center
Zcore	average vortex core radius in spanwise direction
α	temperature coefficient of resistance
Γ,Cr	circulation
Δ	node spacing
δ	boundary layer thickness, yaw angle
μ	viscosity
ρ_{inj}	injectant density
ρ_∞	freestream density
σ	total normal stress
σ'	Reynolds normal stress
τ	total shear stress
τ'	Reynolds shear stress
ν	kinematic viscosity
ψ	effective wire angle
ω_x	streamwise vorticity

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I. INTRODUCTION

A. BACKGROUND

In a film cooled gas turbine engine, significant disturbances to the cooling film result from the interaction between the injectant and the embedded vortices in the gas stream. These disturbances result in local hot-spots that would otherwise be protected by the cooling film. Measurement of these interactions is necessary in order to understand the turbulence structure. This will eventually lead to a means to minimize the negative effects, allowing the development of better designs and more efficient engines.

A study of embedded vortices and wall jet interactions was conducted by Green [Ref. 1]. He measured the turbulence structure resulting from the interactions when the vortex downwash passes over a single film cooling hole. He concluded that embedded vortices significantly distort the injectant turbulence characteristics, thereby altering its turbulent transport properties. The present study is a continuation of Green's work. In addition to vortex downwash measurements, measurements at different blowing ratios are presented when the vortex upwash passes above the injection hole.

To the best knowledge of the author, Green's work [Ref. 1] is the only attempt to measure the turbulence structure of vortex/wall jet interactions. Several researchers have measured the turbulence structure of embedded vortices without wall jets. Of these, Shabaka, Mehta and Bradshaw [Ref. 3] studied the characteristics of a single vortex embedded in a turbulent boundary layer. They concluded that the vortex changes the properties of the outer region of the boundary layer. Cutler and Bradshaw [Ref. 4] studied the interaction of vortex pairs with common flow downward in a turbulent boundary layer. Mehta and Bradshaw [Ref. 5] studied interaction of vortex pairs with common flow upward. The two studies show that turbulence structure changes cannot be explained using current turbulence models, and that secondary longitudinal vortices exist having opposite rotational direction to the principle vortices.

Eibeck and Eaton [Ref. 6] studied the heat transfer and fluid dynamic behavior of a turbulent boundary layer with an embedded vortex. Mean velocity profiles in the log-law region are similar to those in two-dimensional turbulent boundary layers. However, as for the Shabaka et al. [Ref. 3] study, the region outside of the boundary layer log-law region was observed to be significantly distorted by the vortices.

Westphal, Pauley, and Eaton [Ref. 7] made measurements of a single vortex interacting with a turbulent boundary

layer. They obtained mean and turbulent velocity results similar to Shabaka et al. [Ref. 3]. They observed that the skin friction increased under the vortex downwash and decreased under the vortex upwash.

The interaction of vortices and wall jets has also been studied by Skow and Peake [Ref. 8], Heffernan [Ref. 9], Schwartz [Ref. 10], Iwanski, et al. [Ref. 11], Visser, et al. [Ref. 12], Ligrani and Schwartz [Ref. 13], and Ligrani and Williams [Ref. 14]. Most of these studies emphasize heat transfer perturbations or vortex control, and none present detailed turbulence measurements.

B. OBJECTIVES

The purpose of the present study is to obtain further information on the turbulence structure resulting from the interactions between an embedded vortex and a single wall jet. A vortex is created using a vortex generator delta wing placed at a 12 degree angle with streamwise flow. The vortex is positioned so that either the downwash or the upwash is located over the injection hole. Information on the streamwise development of the turbulent structure is obtained from measurements at four streamwise locations, A' ($x'/d = 5.9$), A'' ($x'/d = 19.2$), B ($x'/d = 30.1$), and C ($x'/d = 70.3$).

Blowing ratio m, is defined as the ratio of injectant mass flux to freestream mass flux. For the upwash studies,

blowing ratios of 0 (no blowing), 0.5, 1.5, 2.5, and 3.5 are used in order to study the effect of varying blowing ratio. For downwash studies, data are obtained for blowing ratios of 0 and 1.5 in order to compare with previous data.

C. EXPERIMENTAL APPROACH

First, data showing the streamwise development of the turbulent boundary layer with injection at a blowing ratio of 1.5 and no vortex are presented. Next, baseline measurements of the turbulence structure with no injectant and the vortex downwash over the injection hole are given. These measurements provide confirmation of the operation of the experimental apparatus. Lastly, data are presented to illustrate the interactions between vortices and wall jets. These results are given for one streamwise station with the vortex upwash located over the injection site for a range of blowing ratios.

A free stream velocity of 10 m/s is used for all measurements. The boundary layer is tripped 1.08 m upstream of the wall jet as shown in Figure 1. For downwash measurements, the leading edge of the vortex generator is placed 0.487 m downstream of the boundary layer trip, 0.011 m off the tunnel centerline, and at an angle of 12 degrees with respect to tunnel centerline (Figures 2 and 3). For upwash studies the vortex generator is moved to 0.047 m off tunnel centerline using the same streamwise location and

angle (Figures 2 and 4). The jet issues from a 0.952 cm diameter hole located at the centerline of the tunnel and inclined 30 degrees with respect to the horizontal test surface. The ratio of boundary layer displacement thickness to injection hole diameter is equal to 0.28 at the injection site.

A crossed hot-wire probe is used to measure mean and instantaneous velocity components in spanwise normal planes. Measurements are taken at four different streamwise locations.

D. THESIS OUTLINE

Chapter I gives introduction and motivation for research. Chapter II describes the wind tunnel, injection system, vortex generator and other equipment. Chapter III gives an overview of the hot-wire anemometer, data acquisition, micro-computer and probe traversing system. Results of experiments are given in Chapter IV and conclusions are in Chapter V. A software directory is given in Appendix A. A Data Directory is contained in Appendix B. Appendix C contains all the figures and plots generated by this study.

II. EXPERIMENTAL APPARATUS

A. WIND TUNNEL AND TEST SECTION

Experiments were conducted using the same wind tunnel described by Green [Ref. 1: pp. 6-8]. A detailed description of this wind tunnel will not be repeated here. The wind tunnel was manufactured by Aerolab and is located in the laboratories of the Mechanical Engineering Department of the Naval Postgraduate School. The freestream turbulence intensity is about 0.20 percent, for freestream velocities of 10 m/s. The boundary layer is tripped to become fully turbulent at the entrance to the test section with a 1.5 mm high strip of tape. A schematic of the test section is shown in Figure 1.

The right handed coordinate system is also shown in Figure 1. Its origin is located on the floor of the test section where the turbulence trip intersects the spanwise centerline. The positive x direction is measured downstream from the trip. The positive y direction is measured upward from the test surface. The positive z direction is measured to the right of centerline as looking downstream. The four downstream locations of data collection (labeled A', A'', B and C) are also shown in Figure 1. Location of injection holes, Kiel probe, and thermocouple are also shown. Further

information concerning the wind tunnel and testing may be found in [Ref. 2: pp. 38-40].

B. VORTEX GENERATOR

A half delta wing is used to generate the single longitudinal vortex. Figures 2 and 3 show the placement of the delta wing on the test surface so that the vortex downwash passes over the injection hole. Figure 4 shows the position of the delta wing so that the vortex upwash passes over the injection hole. This generator is the same one employed by Green [Ref. 1].

C. INJECTION SYSTEM

The air injection system is also described by Green [Ref. 1: pp. 6-8] with the exception of the air supply. In the present study, the Ingersol-Rand air compressor used in Green's work, is replaced by a 1.5 hp, 2.5 psig, 30 scfm EG&G ROTRON regenerative blower. The discharge of the blower flows into an aluminum plenum measuring 18 in x 18 in x 18 in. The outlet of this plenum is connected to the globe valve and rotometer, and other apparatus described by Green.

III. HOT-WIRE ANEMOMETER AND DATA ACQUISITION SYSTEM

The same data acquisition system and same type of crossed hot wire anemometer probe are used in this study as described by Green [Ref. 1:pp. 9-20] and Subramanian et al. [Ref. 15]. A schematic of the system employed to obtain the measurements is shown in Figure 5. A brief description follows.

A. CROSSED HOT-WIRE SYSTEM

1. Crossed Hot-wire Probe

The crossed hot-wire probe, Type 55 P51, is made by DANTEC Electronics Inc. The 5 μm wires are made of 90% platinum and 10% rhodium. They are mounted perpendicular to each other with about 1 mm separating them. Each wire is about 1 mm long with a "cold" resistance of about 4.1 ohms at room temperature. An operating overheat ratio of 1.8 is used for all experiments. The probe and holder are supported by a vertical stem which are mounted on a traversing device that moves the probe in the y-z plane. The probe can also be rotated about the stem (y axis) for yaw calibration.

2. Hot-wire Anemometer and Signal Conditioner

Two DANTEC 55M10 constant temperature bridges are used to operate the crossed hot-wires (one for each wire).

The probe and connecting cable "cold" wire resistances are measured on the decade counter by balancing the bridge. The operating resistance is then set to 1.8 times the cold wire resistance.

A DANTEC 56N20 two channel signal conditioner is used to low pass filter using a 10 kHz cut off frequency and to amplify signals from the bridges. The operating range of the high speed analog-to-digital converter is optimized by using a gain of 2 without any DC offset. The low pass filter is used to eliminate noise. The high pass setting on the signal conditioner is set to "DC" in order to include the DC component and low frequency velocity variations of the signal.

B. DATA ACQUISITION SYSTEM

1. Low Speed Data Acquisition

For low speed data acquisition and analog-to-digital conversion, a Hewlett-Packard 3497A control unit is used. Readings obtained by the low speed data acquisition system include ones from a Kiel probe and electronic manometer, freestream and injection thermocouples, and hot-wire anemometer voltage signals during probe calibration. A sample size of 50 is taken with a 5 Hz sampling frequency. Temperature and pressure data are read by the low speed data acquisition system during probe calibration as well as during turbulence measurements.

2. High Speed Analog-to-digital Converter

A Hewlett-packard 6944A Multiprogrammer with a buffered 69759A A/D card is used to convert analog turbulence signals from the signal conditioner to digital signals. The buffer feature allows digitized data to be stored while the computer is performing other tasks. Continuous data acquisition is accomplished as long as the computer reads the data out of the buffer faster than it is being written.

The sampling rate and the number of samples collected at each data point are set so that converged time-averaged velocity values are obtained. A sampling frequency of 5000 Hz per channel and a sample size of 20,000 samples per channel are employed. This combination results in four seconds of real sample time per channel at each data point. Increasing the sample size dramatically increases computer run time. Lowering the sampling frequency results in less resolution of small time scale turbulence effects.

The high speed analog-to-digital converter card reads analog inputs and converts them to 12-bit binary numbers. The card is configured to measure analog inputs ranging from -10.240 V to +10.235 V. This 20.475 V input range is divided into 4096 increments of 0.005 V size.

C. CALIBRATION

The instantaneous velocities U and V (and W) are calculated using Equation (1). A different form of this equation is determined for the signal from each wire giving a system of two equations which are solved for two unknown velocities.

$$U_{eff} = U \cos \psi + V \sin \psi = K(E^2 - E_{oc}^2)^{1/n} \quad (1)$$

Coefficients K, ψ, and n are constants determined from the sensor calibration. E_{oc} is the effective bridge voltage at zero velocity extrapolated from the forced convection calibration. The effective wire angle is denoted ψ. Calibration is a three step process including: velocity and yaw calibration in the uw plane, and velocity calibration in the uv plane.

1. Velocity Calibration in the uw Plane

By rearranging Equation (1) and defining a coefficient, B:

$$B = (\cos \psi / K)^n \quad (2)$$

a relationship between E and U is obtained, given by:

$$E^2 = E_{oc}^2 + B\, U^n \quad (3)$$

Based on Collis and Williams [Ref. 16], n is set equal to 0.45. From the flow velocity, U, and bridge voltages, E, a least squares fit can be used to find B and E_{oc}^2.

2. Yaw Calibration

The value of K can be determined from Equation (2) if the effective wire angle ψ is known. Yaw calibration involves moving the probe through a series of known angles in the x-z plane (V = 0) with the probe exposed to a constant flow velocity. At a yaw angle, δ, Equation (1) then becomes:

$$U \cos(\psi + \delta) = K(E_\delta^2 - E_{oc}^2)^{1/n} \tag{4}$$

where E_δ is the bridge voltage at yaw angle δ. From Equation (1) with zero yaw angle:

$$K = \frac{U \cos \psi}{(E^2 - E_{oc}^2)^{1/n}} \tag{5}$$

where E equals the bridge voltage when yaw angle is equal to zero. Replacing K in Equation (4) with Equation (5) and rearranging then gives:

$$\tan \psi = (\cos \delta - [(E_\delta^2 - E_{oc}^2)/(E^2 - E_{oc}^2)]^{1/n})/\sin \delta \tag{6}$$

Effective wire angles are subsequently determined directly from Equation (6) after the probe is yawed through six different values of δ. The final ψ for each wire is then the average of the six ψ's calculated at the six yaw angles.

3. Velocity Calibration in the uv Plane

For the uv plane measurements, the wire constants from the uw plane calibrations are corrected for possible probe pitching when the probe was rotated from uw to uv plane. This is done as follows. The velocity calibration explained in Section III.C.1 is repeated with the probe in the uv plane. The zero flow voltage E_{oc}, and the power law index, n, are assumed to be the same as determined from the uw plane calibration. Then, from a linear least square fit of

$$[E^2 - E_{oc}{}^2] \text{ vs } U^{0.45}$$

the slope of the line, B_{uv} is obtained. Then, the wire angle in the uv plane ψ_{uv} is found from

$$\cos \psi_{uv} = k/B_{uv}$$

where k is given by Equation (5) for the uw plane.

D. MICROCOMPUTER

A Hewlett-Packard Series 9000 computer is the central brain of the system. The computer is equipped with interfaces connected to the HP 6944A multiprogrammer with a high speed analog-to-digital converter and a buffer, the low speed data acquisition system, and the traverse motor controller. The computer reads data from the buffer in the multiprogrammer, performs on line data reduction and controls the position of the probe. Reduced data are stored on a 3.5" disk for future use.

1. Data Reduction

At each node, 20,000 samples per channel are collected. With 228 nodes and two channels, over 9.1 million samples are collected per survey.

a. Hot-wire Temperature Drift Correction

The freestream air temperature does not remain constant during the 12 hours required to complete one survey. Since the calibration constants depend on the "cold" wire resistance at the freestream air temperature during calibration, hot-wire calibration will change due to this freestream temperature drift. To correct for these variations the measured bridge voltage, E, is corrected using:

$$E_{corr} = E(1 + C) \tag{7}$$

where C is given by:

$$C = \alpha(T_\alpha - T_{cal})/[2(OHR - 1)] \qquad (8)$$

where α is the temperature coefficient of resistance and is equal to 0.0034/C for the wire material, OHR is the overheat ratio, T_α is the freestream temperature and T_{cal} is the freestream temperature at time of calibration.

b. Look-up Table

In order to save computer time and speed up data reduction, a look-up table is constructed. The look-up table contains one effective velocity for each of the 4096 binary values assigned to voltages by the high speed analog-to-digital converter. This means that Equation (1), which requires time-consuming exponential calculations, is used only 4096 times to calculate effective velocities from voltages rather than 9.1 million times. When the table is used, the computer simply reads a binary value from the high speed analog-to-digital converter, finds this value in the look-up table then reads the corresponding effective velocity. The look-up table includes the hot wire system gains as well as the temperature drift corrections. The look-up table contains two effective velocity arrays, one for each of the crossed wires. With the effective velocities known for each wire, the instantaneous velocities, U and V, can be calculated from Equation (1).

c. Turbulence Statistics

Because computer memory limits array size to 2000 elements, data collection is done in ten loops in order to achieve the 20,000 samples per wire per data point. Turbulence statistics are calculated and averaged for each loop. The averages from the ten loops are then averaged.

Turbulent statistics are calculated using the following equations. By replacing the subscript v with w and upper case V with W, the following equations can also be used for the uw plane calculations.

$$\bar{u} = S_u$$

$$\bar{v} = S_v$$

$$\overline{u'^2} = S_{uu} - S_u S_u$$

$$\overline{v'^2} = S_{vv} - S_v S_v$$

$$\overline{u'v'} = S_{\overline{u'v'}} - S_u S_v \qquad (9)$$

$$\overline{(u')^2 v'} = S_{uuv} - S_v(S_u S_u - (u')^2) - 2S_u\overline{u'v'}$$

$$\overline{u'(v')^2} = S_{uvv} - S_u(S_v S_v - (v')^2) - 2S_v\overline{u'v'}$$

$$\overline{u'^3} = S_{uuu} - S_u(S_u S_u + 3(u')^2)$$

$$\overline{v'^3} = S_{vvv} - S_v(S_v S_v + 3(v')^2)$$

where:

$$S_u = \frac{1}{20,000} \sum_{loop=1}^{10} \sum_{sample=1}^{2000} U$$

$$S_v = \frac{1}{20,000} \sum_{loop=1}^{10} \sum_{sample=1}^{2000} V$$

$$S_{uu} = \frac{1}{20,000} \sum_{loop=1}^{10} \sum_{sample=1}^{2000} UU$$

$$S_{vv} = \frac{1}{20,000} \sum_{loop=1}^{10} \sum_{sample=1}^{2000} VV$$

$$S_{\overline{u'v'}} = \frac{1}{20,000} \sum_{loop=1}^{10} \sum_{sample=1}^{2000} UV \qquad (10)$$

$$S_{uuv} = \frac{1}{20,000} \sum_{loop=1}^{10} \sum_{sample=1}^{2000} UUV$$

$$S_{uvv} = \frac{1}{20,000} \sum_{loop=1}^{10} \sum_{sample=1}^{2000} UVV$$

$$S_{uuu} = \frac{1}{20,000} \sum_{loop=1}^{10} \sum_{sample=1}^{2000} UUU$$

$$S_{vvv} = \frac{1}{20,000} \sum_{loop=1}^{10} \sum_{sample=1}^{2000} VVV$$

In these equations, U and V are instantaneous velocities.

2. Probe Traversing

The microcomputer controls the position of the probe through a MODULYNX MITAS controller (type PMS085-C2AR) which drives two D.C. motors, which move the probe in the y and z directions. For all but two surveys, the probe is traversed through a 3.0 inch x 4.5 inch plane. The area of these surveys are covered with a 12 node by 19 node matrix with vertical and horizontal node spacing of 0.25 inches. The additional two surveys are conducted using 304 nodes with a 16 node x 19 node matrix and a spacing of 0.10 inches, which gives a 1.5 inch x 1.8 inch plane.

IV. EXPERIMENTAL RESULTS

A. CALCULATIONS

All calculations are performed using the same software as Green [Ref. 1]. A directory of this software is presented in Appendix A. All results are displayed in graphical form.

1. Normalization of Results

Freestream velocity is used to normalize Reynolds stress tensor components, average velocities and triple products. To normalize data from each column of nodes, the freestream velocity is measured at the top of each column. This accounts for small variations in freestream velocity over the 12 hour period required to complete a 228 node survey. The location of this freestream velocity measurement is well outside the boundary layer and the regions influenced by the vortices.

2. Streamwise Vorticity

Streamwise vorticity is estimated using the center-finite-difference method at each node. Green [Ref. 1:p. 22] provides additional details.

3. Circulation

Circulation is estimated using the method described by Schwartz [Ref. 10: pp. 17-18]. Circulation is calculated by multiplying the vorticity at each node by the area around

that node and then summing this product over all nodes that exceed the threshold. The threshold level is established so that background "noise" from estimation of velocity derivatives does not influence the estimation of circulation. These calculations are described in detail by Green [Ref. 1:p. 22]. Circulation is denoted Cr in the listings on each vorticity plot.

4. Vortex Core Size

Vortex core size is estimated using the two methods described by Green [Ref. 1:p. 23]. The resulting Ycore and Zcore values from these methods are also listed on the vorticity plots.

B. SURVEY CONDITIONS AND PARAMETERS

Table 1, below, gives the conditions of each survey conducted. Discussion of results will proceed in the same order as presented in Table 1.

C. BASELINE DATA

1. Streamwise Development of Boundary Layer with Injection Only

Figures 6-69 show the streamwise development of the boundary layer with injection from a single hole at a blowing ratio of 1.5. The location of the four streamwise measurement locations and the coordinate system are shown in Figure 1. The interaction of the jet with the boundary

TABLE 1

SUMMARY OF SURVEY CONDITIONS AND PARAMETERS

Run # Date.Time	Probe Loc.	Probe Orient.	Node Spacing	Blowing Ratio	Vortex Gen.	Figure Num.
61789.1949	A'	uv	0.25	1.5	NONE	6-21
61889.0745	A'	uw	0.25	1.5	NONE	
61689.1711	A''	uv	0.25	1.5	NONE	22-37
61789.0647	A''	uw	0.25	1.5	NONE	
61589.0844	B	uv	0.25	1.5	NONE	38-53
61589.2121	B	uw	0.25	1.5	NONE	
61889.1951	C	uv	0.25	1.5	NONE	54-69
61989.0755	C	uw	0.25	1.5	NONE	
60789.2054	A'	uv	0.25	0	DW	70-85
60889.0854	A'	uw	0.25	0	DW	
60689.1107	A''	uv	0.25	0	DW	86-101
60789.0704	A''	uw	0.25	0	DW	
61089.0743	B	uv	0.10	0	DW	102-117
61289.0813	B	uw	0.10	0	DW	
60889.2049	C	uv	0.25	0	DW	118-133
60989.1219	C	uw	0.25	0	DW	
72189.0931	B	uv	0.25	0	UW	134-149
72289.0831	B	uw	0.25	0	UW	
71089.1212	B	uv	0.10	1.5	DW	150-165
71189.1220	B	uw	0.10	1.5	DW	
60189.1156	B	uv	0.25	0.5	UW	166-181
60289.0927	B	uw	0.25	0.5	UW	
60389.0655	B	uv	0.25	1.5	UW	182-197
60389.1901	B	uw	0.25	1.5	UW	
60489.0652	B	uv	0.25	2.5	UW	198-213
60489.1856	B	uw	0.25	2.5	UW	
60589.0715	B	uv	0.25	3.5	UW	214-229
60589.1918	B	uw	0.25	3.5	UW	

NOTES:

1. Freestream velocity U_∞ =10 m/s
2. Probe locations (x'/d): A' = 5.9, A'' = 19.2, B = 30.1, and C = 70.3
3. Downwash Vortex Generator: 12 degrees with leading edge at x = 48.7 cm and z = 1.0 cm
4. Upwash Vortex Generator: 12 degrees with leading edge at x = 48.7 cm and z = 4.7 cm

layer is the strongest at the measuring location closest to the injection site (station A').

Mean velocities, the three normal Reynolds stress components and two Reynolds shear stress components are distorted significantly by the jet. Normal stresses show completely different character compared to shear stresses as injectant is convected downstream. In this regard, normal stresses show maximum values near the center of the injection jet. Mean velocities, shear stresses and longitudinal vorticity distributions provide evidence that boundary layer fluid wraps around the jet to form a structure similar to a vortex pair. Because of the secondary flows within this structure, distributions of $\overline{u'v'}$ and $\overline{u'w'}$ at $x'/d = 5.9$ show quite complicated variations. Some of the contours in the proximity of the jet are dome shaped. This pattern is centered along the jet axis ($z = 0$) and seen in the plots of $\overline{v'^3}$, $\overline{u'^2v'}$, and $\overline{u'v'^2}$.

The vortex-like structure on the +z side rotates clockwise as looking downstream (+x direction), and the matching vortex on the -z side rotates in a counter-clockwise direction. The effect of this vortex pair is to convect low-velocity fluid away from the wall at $z = 0$ and to convect high-velocity freestream fluid towards the wall at z locations of 1.5 to 3.0 cm and -1.5 to -3.0 cm. As expected, this vortex pair structure grows in size and decreases in intensity as it progresses downstream. Both

vortices have a region of large positive $\overline{u'^3}$, with a region of large negative $\overline{u'^3}$ between them near the wall.

Contours of $\overline{u'v'}$ at x'/d = 5.9 show double positive peaks which exist above a region of negative u'v'. The values of these peaks are about $0.004U_e^2$ or $0.003U_e^2$. Because of these peaks, the shear stress distribution shows a shape which is flattened in the spanwise direction. Shear stress levels beneath the double peak (near the wall) are also lower than in the surrounding undisturbed boundary layer. In a turbulent boundary layer with a two-dimensional mean flow field, positive shear stresses do not exist. In this situation, a typical minimum value of $\overline{u'v'}$ is $-0.0028U_e^2$.

Positive $\overline{u'v'}$ shear stress regions are not noticeable for x'/d of 19.2, 30.1 and 70.3. At these streamwise stations, negative shear stresses extend in the vertical direction away from the wall. Shear stress levels are also quite small along the axis of the jet because of minimal turbulence production.

Distributions of $\overline{u'w'}$ are very interesting since there are high stress levels around the jet, and strong gradients of positive and negative stresses, especially for x'/d = 5.9. Symmetric contours are evident about the jet centerplane, especially for the last three streamwise stations. At the first three streamwise stations, a pair of positive shear stress regions and a pair of negative shear stress regions are evident. For x'/d > 5.9 the inner pair

grows vertically as absolute values of shear stress diminish. The outer pair is then pushed in the spanwise direction as this occurs. Interestingly, the general characteristics of $\overline{u'w'}$ development show some similarity to the development of mean streamwise vorticity.

In the clockwise vortex, the spanwise shear, $\overline{u'w'}$, shows large negative values while the triple products $\overline{w'^3}$ and $\overline{u'^2w'}$ show large positive values. In the counter-clockwise vortex, $\overline{u'w'}$ is positive and $\overline{w'^3}$ and $\overline{u'^2w'}$ are negative. Very little disturbance to the boundary layer is noted at spanwise locations for z less than about -4.0 cm.

2. Streamwise Development of the Boundary Layer with a Single Embedded Vortex and No Film Injection

Data showing the effects of the interactions between a vortex and the boundary layer are shown in Figures 70-149. Figures 70-133 show streamwise development when the vortex downwash passes over the injection hole (see Figure 3). Figures 102-117 are present results of a detail survey at station B when a node spacing of 0.10 inches is employed to provide greater degree of spatial resolution of the measured quantities. Figures 134-149 present data obtained when the vortex upwash passes over the injection hole.

As expected, data in Figures 70-133 show that the vortex center moves to the left (-z direction) and upward (+y direction) as the flow progresses downstream. The vortex core size remains approximately constant.

Circulation decreases as the vortex energy is dissipated. Table 2 lists the location of the core center, the average core size and the circulation for each measurement station.

TABLE 2

LOCATION OF CORE CENTER AND SIZE IN BOUNDARY LAYER WITH VORTEX ONLY

STATION	CORE CENTER z(cm),y(cm)	AVERAGE CORE SIZE (cm)	CIRCULATION (s^{-1})
A'	-1.9,2.5	0.74	0.10230
A''	-2.5,2.5	0.71	0.09574
B	-2.9,2.8	NA	NA
C	-4.4,3.1	0.77	0.08121

NOTES:
1. Average core radius using 40% of $\omega_x$max criterion
2. Station B core size and circulation not calculated

The three primary regions of the vortex are the core, downwash region and upwash region. Boundary layer thinning in the downwash region results as high velocity fluid is convected toward the wall. The boundary layer is thickened in the vortex upwash region as slower moving fluid is convected away from the wall.

At station A', the normal Reynolds stress components $\overline{u'^2}$, $\overline{v'^2}$, and $\overline{w'^2}$ show large gradients in the vortex core. Two regions of large positive Reynolds shear stress, $\overline{u'w'}$, are separated by a region of large negative Reynolds shear stress. The triple products show large gradients not only

at the vortex core, but also, near the wall in the downwash region.

Data for station B from the survey with 0.10 inch node spacing provides additional information on the detailed structure of the flow. Here, the triple products show severe gradients in the vortex core that are not apparent in the surveys when a 0.25 inch node spacing is used.

Data in Figures 134-149 for position B show flow properties for a different spanwise vortex location. These results are similar to ones obtained when the vortex downwash passes over the injection hole, except the vortex center shifts 3.6 cm to the right when compared to the downwash case.

D. BOUNDARY LAYER/VORTEX/WALL JET INTERACTIONS

Data showing the interactions between the vortex and wall jet are presented for station B which is equivalent to x'/d of 30.1. Figures 150-165 show results of a survey (node spacing of 0.10 inches) conducted when the vortex downwash passes above the injection location. Figures 166-229 then give data showing the effects of blowing ratio when the vortex upwash passes over the injection location.

1. Vortex Downwash Passes Over the Injection Hole, m = 1.5

In Figures 150-165, it is apparent that the vortex center moves away from the wall because of the walljet. The size of the core of this primary vortex is about the same as

with no blowing. A weak secondary vortex also develops which is seen in Figure 165. This region of negative vorticity is centered at y = 0.87 cm and z = -6.25 cm and corresponds to an area of high streamwise velocity.

Results in Figures 150-165 also show large gradients of $\overline{u'v'}$ and all triple products in or near the vortex core which are not apparent in the surveys where a 0.25 inch node spacing is used. These regions of high Reynolds shear stress tend to become enlarged because of the jet. The jet also causes dome-shaped regions near the wall, centered at z = -3.0 cm, in plots of $\bar{u}$, $\overline{u'v'}$, $\overline{u'w'}$, $\overline{u'^2w'}$ and $\overline{u'^3}$

2. Vortex Upwash Passes Over the Injection Hole, m = 0.5, 1.5, 2.5 and 3.5

Figures 166-229 show the effects of varying blowing ratio on the boundary layer when the vortex upwash passes over the injection site. Table 3 gives circulation and core radius values for the different blowing ratios. From these data, it is evident that circulation increases as blowing ratio increases. A region of negative vorticity develops near the wall at low blowing ratios. As blowing ratio increases, this negative vorticity region increases in size and intensity. The region moves upward as blowing ratio increases and more fluid is convected away from the wall.

Data for blowing ratios of 0.5 and 1.5 show qualitative behavior typical of vortices uninfluenced by wall jets. Large gradients of the Reynolds shear stresses and most

TABLE 3

CORE RADIUS, CIRCULATION AND STREAMWISE VORTICITY OF BOUNDARY LAYER WITH VORTEX UPWASH ABOVE JET

BLOWING RATIO	CORE RADIUS (cm)	CIRCULATION (m^2/s)	STREAMWISE VORTICITY (s^{-1})
0.5	0.77	0.10175	503.8
1.5	0.75	0.10622	550.1
2.5	0.91	0.13010	461.2
3.5	1.02	0.14247	437.0

triple products exist near the core. With blowing ratios of 0.5 and 1.5, contour plots of $\overline{u'^2}$, $\overline{v'^2}$, $\overline{w'^2}$, $\overline{u'v'}$, and $\overline{u'w'}$ also show dome-shaped variations near z = -1.25 cm. Similar behavior is evident in regard to the triple products. The dome-shaped regions are characterized by large positive values near the wall. As blowing ratio increases, spatial extents and magnitudes of properties of these regions then increase.

With blowing ratios of 2.5 and 3.5, data indicate that the jet is more influential than the vortex in regard to local flow behavior. Because of the walljet, the vortex is pushed away from the wall and contour plots show mushroom-shaped variations. The vortex core grows in size and is displaced upward. Severe gradients of $\overline{u'v'}$, $\overline{u'w'}$ and triple products develop in the core, which separate negative and positive regions.

V. SUMMARY AND CONCLUSIONS

The turbulent structure as a result of the interaction of an embedded vortex and a single wall jet was investigated. Measurements of the streamwise development of the boundary layer as influenced by a jet only and by a vortex only were conducted to verify and clarify earlier work. The effects of a jet on the boundary layer with an embedded vortex with the upwash passing over the jet were also investigated. The vortex was generated using a 12 degree delta wing mounted on the test section floor. Blowing ratios varied from 0.5 to 3.5. Freestream velocity was 10 m/s, as provided in a zero pressure gradient.

The vortex significantly alters the turbulence structure of the wall jet and vice versa. At blowing ratios of 1.5 and less, the injectant is distorted and convected away from the injection hole by vortex secondary flows. At blowing ratios above 1.5,the jet dominates the flow causing the vortex to be displaced away from the wall. Because of the jet, Reynolds shear stress components, $\overline{u'v'}$ and $\overline{u'w'}$ show severe gradients near the vortex core. When the vortex upwash passes over the injection location, a region of negative vorticity develops because of the jet, which grows in intensity and is displaced away from the wall as the blowing ratio increases.

Mean velocities, and the three normal Reynolds stress components are distorted significantly by a 1.5 blowing ratio when no vortex is present. Normal stresses show completely different character compared to shear stresses as injectant is convected downstream. In this regard, normal stresses show maximum values near the center of the injection jet. Mean velocities, shear stresses and longitudinal vorticity distributions provide evidence that boundary layer fluid wraps around the jet to form a structure similar to a vortex pair. Because of the secondary flows within this structure, distributions of $\overline{u'v'}$ and $\overline{u'w'}$ at $x'/d = 5.9$ show quite complicated variations.

APPENDIX A

SOFTWARE DIRECTORY

Calibration, data acquisition and plotting programs are written in the HP-BASIC language. Program names and descriptions follow.

Program Name	Description
HWCAL300	Performs velocity and yaw calibration for the crossed wire probe. Calibration constants for measurements in uv and uw planes are written to files Cal#UV and Cal#UW respectively. In these file names, # is and integer automatically assigned to index the calibration files.
SETCOND	Calculates blowing ratio, discharge coefficient and freestream velocity before each experiment. User must input total freestream pressure, pressure drop across injection holes, number of injection holes in use and injectant flow rate.
HOTWIREUV	Data acquisition program for measurements in the uv plane. Measures actual system gain and offset. Then constructs look-up table using probe calibration constants read from file Cal#UV. The program includes commands to automatically move the probe through the desired number of nodes at the desired node spacing. Calculates $\bar{u}$, u'^2, $\overline{v'^2}$, $\overline{u'v'}$, $\overline{v'^3}$, $\overline{u'^2v'}$ and $\overline{u'v'^2}$ at each node. The results are written to a data file named by the user. This file is referred to as the uv data file.
HOTWIREUW	Data acquisition program for measurements in the uw plane. Reads probe calibration constants from file Cal#UW and writes results to the uw data file.
AVG	Reads from uv and uw data files and normalizes $\bar{u}$, $\overline{u'^2}$ and $\overline{u'^3}$ at each node with respect to ubar, ubar^2 or ubar^3 measured at

	the top of each column of nodes. Averages normalized quantities from uv and uw data files. Results are plotted in contour format.
Baruv	Reads data from uv data file and plots contours of u and v normalized with respect to ubar measured at the top of each column of nodes.
Baruw	Reads data from uw data file and plots contours of u and w normalized with respect to ubar measured at the top of each column of nodes.
2UV	Reads data from uv data file and plots contours of $\overline{v'^2}$ and $\overline{u'v'}$ normalized with respect to $ubar^2$ measured at the top of each column of nodes.
2UW	Reads data from uw data file and plots contours of $\overline{w'^2}$ and $\overline{u'w'}$ normalized with respect to $ubar^2$ measured at the top of each column of nodes.
3UV	Reads data from uv data file and plots contours of $\overline{v'^3}$ $\overline{u'^2w'}$, and $\overline{u'v'^2}$ normalized with respect to $ubar^3$ measured at the top of each column of nodes.
3UW	Reads data from uw data file and plots contours of $\overline{w'^3}$, $\overline{u'^2w'}$, and $\overline{u'w'^2}$ normalized with respect to $ubar^3$ measured at the top of each column of nodes.

APPENDIX B

DATA DIRECTORY

Run # Date.Time	Probe Loc.	Probe Orient.	Node Spacing	Blowing Ratio	Vortex Gen.	Figure Num.
61789.1949	A'	uv	0.25	1.5	NONE	6-21
61889.0745	A'	uw	0.25	1.5	NONE	
61689.1711	A''	uv	0.25	1.5	NONE	22-37
61789.0647	A''	uw	0.25	1.5	NONE	
61589.0844	B	uv	0.25	1.5	NONE	38-53
61589.2121	B	uw	0.25	1.5	NONE	
61889.1951	C	uv	0.25	1.5	NONE	54-69
61989.0755	C	uw	0.25	1.5	NONE	
60789.2054	A'	uv	0.25	0	DW	70-85
60889.0854	A'	uw	0.25	0	DW	
60689.1107	A''	uv	0.25	0	DW	86-101
60789.0704	A''	uw	0.25	0	DW	
61089.0743	B	uv	0.10	0	DW	102-117
61289.0813	B	uw	0.10	0	DW	
60889.2049	C	uv	0.25	0	DW	118-133
60989.1219	C	uw	0.25	0	DW	
72189.0931	B	uv	0.25	0	UW	134-149
72289.0831	B	uw	0.25	0	UW	
71089.1212	B	uv	0.10	1.5	DW	150-165
71189.1220	B	uw	0.10	1.5	DW	
60189.1156	B	uv	0.25	0.5	UW	166-181
60289.0927	B	uw	0.25	0.5	UW	
60389.0655	B	uv	0.25	1.5	UW	182-197
60389.1901	B	uw	0.25	1.5	UW	
60489.0652	B	uv	0.25	2.5	UW	198-213
60489.1856	B	uw	0.25	2.5	UW	
60589.0715	B	uv	0.25	3.5	UW	214-229
60589.1918	B	uw	0.25	3.5	UW	

NOTES:

1. Freestream velocity U_∞ =10 m/s
2. Probe locations (x'/d): A' = 5.9, A'' = 19.2, B = 30.1, and C = 70.3
3. Downwash Vortex Generator: 12 degrees with leading edge at x = 48.7 cm and z = 1.0 cm
4. Upwash Vortex Generator: 12 degrees with leading edge at x = 48.7 cm and z = 4.7 cm

APPENDIX C

FIGURES

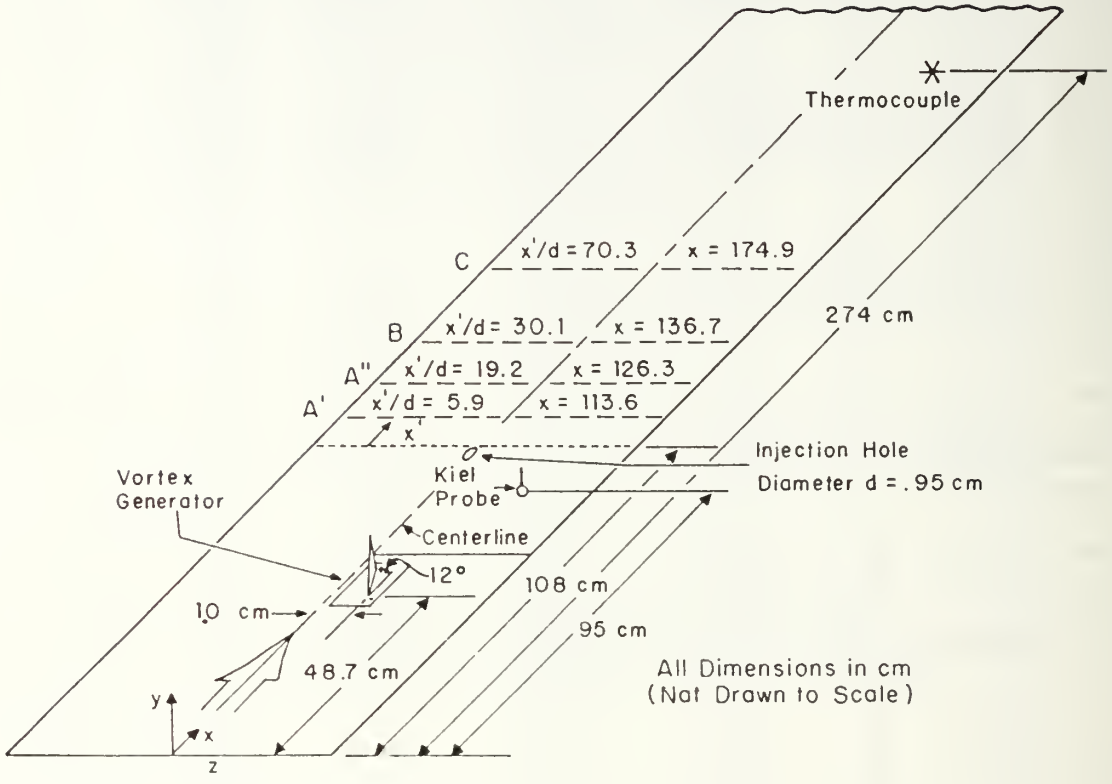

Figure 1. Test Section Schematic

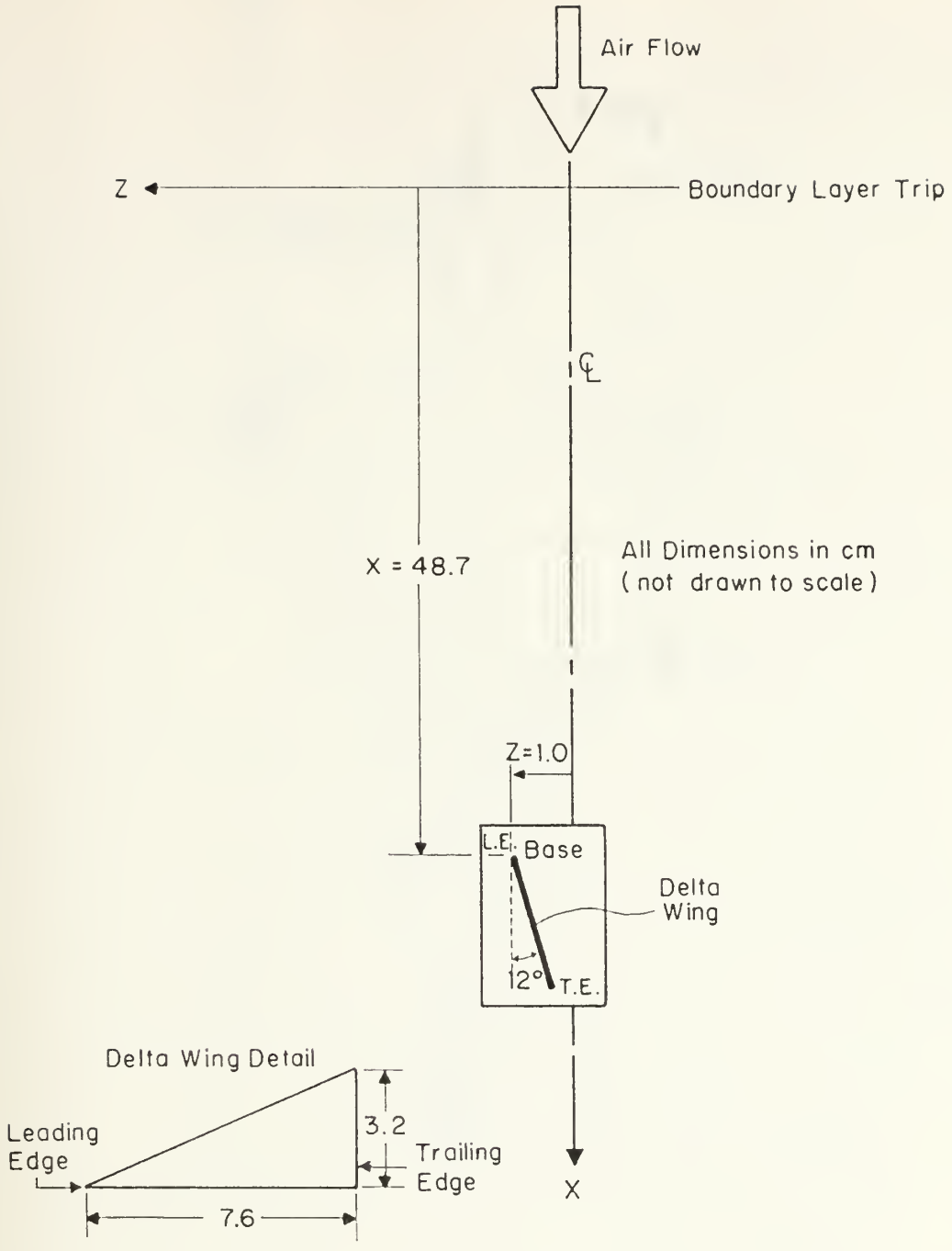

Figure 2. Vortex Generator

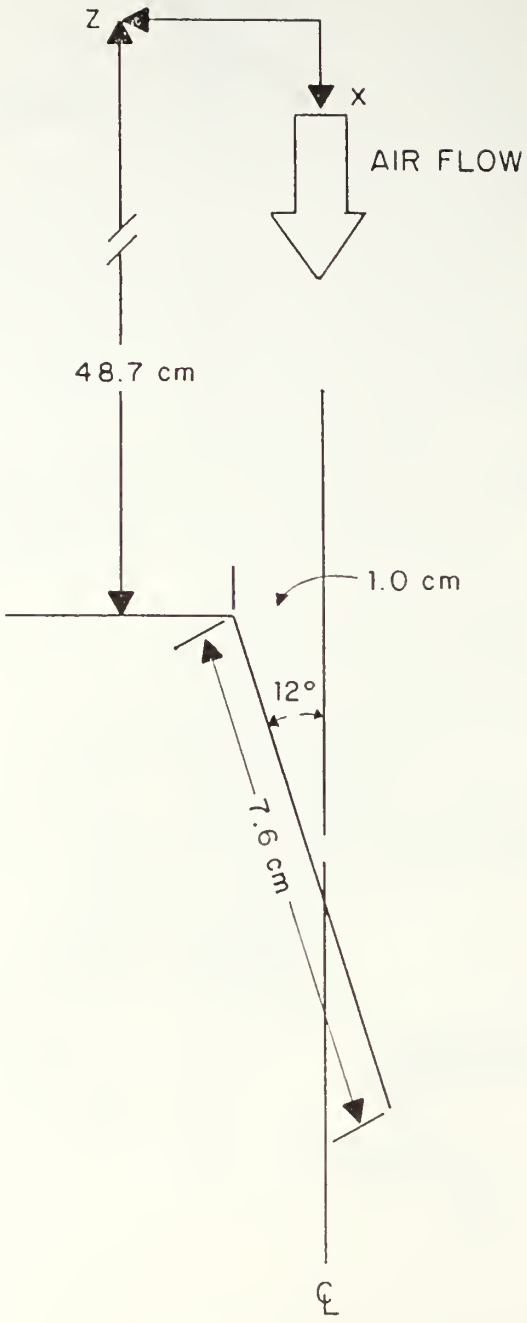

Figure 3. Vortex Generator Downwash Placement

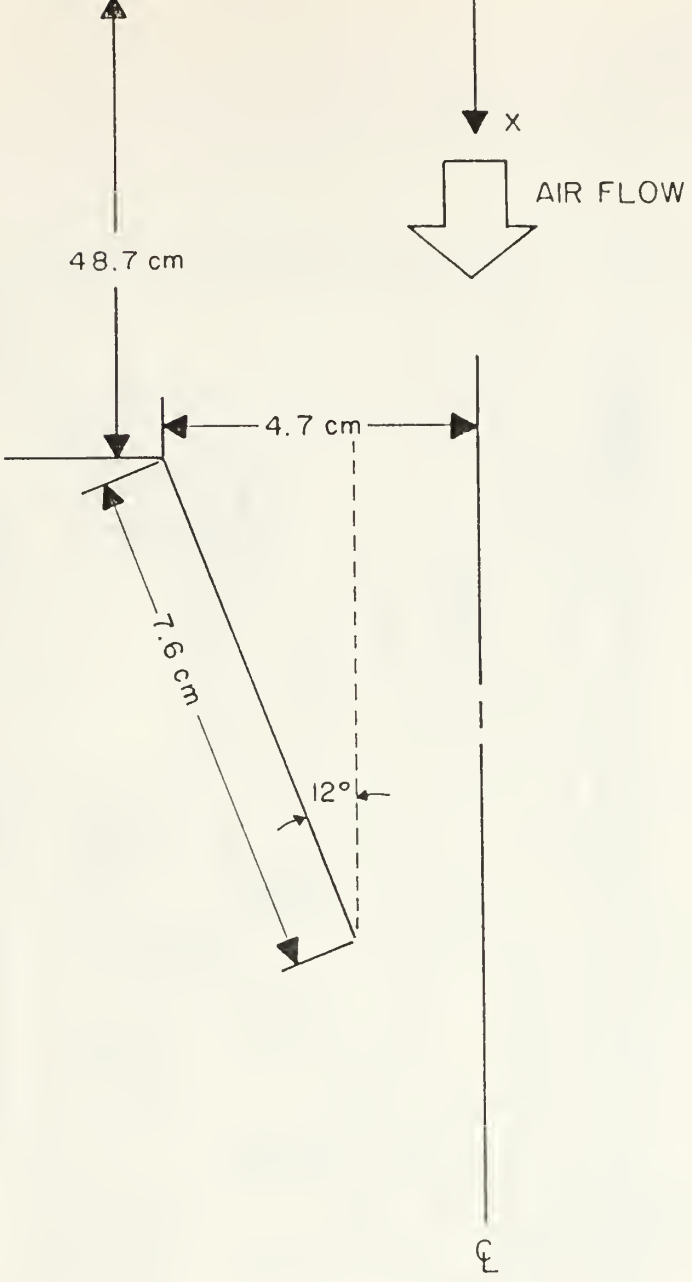

Figure 4. Vortex Generator Upwash Placement

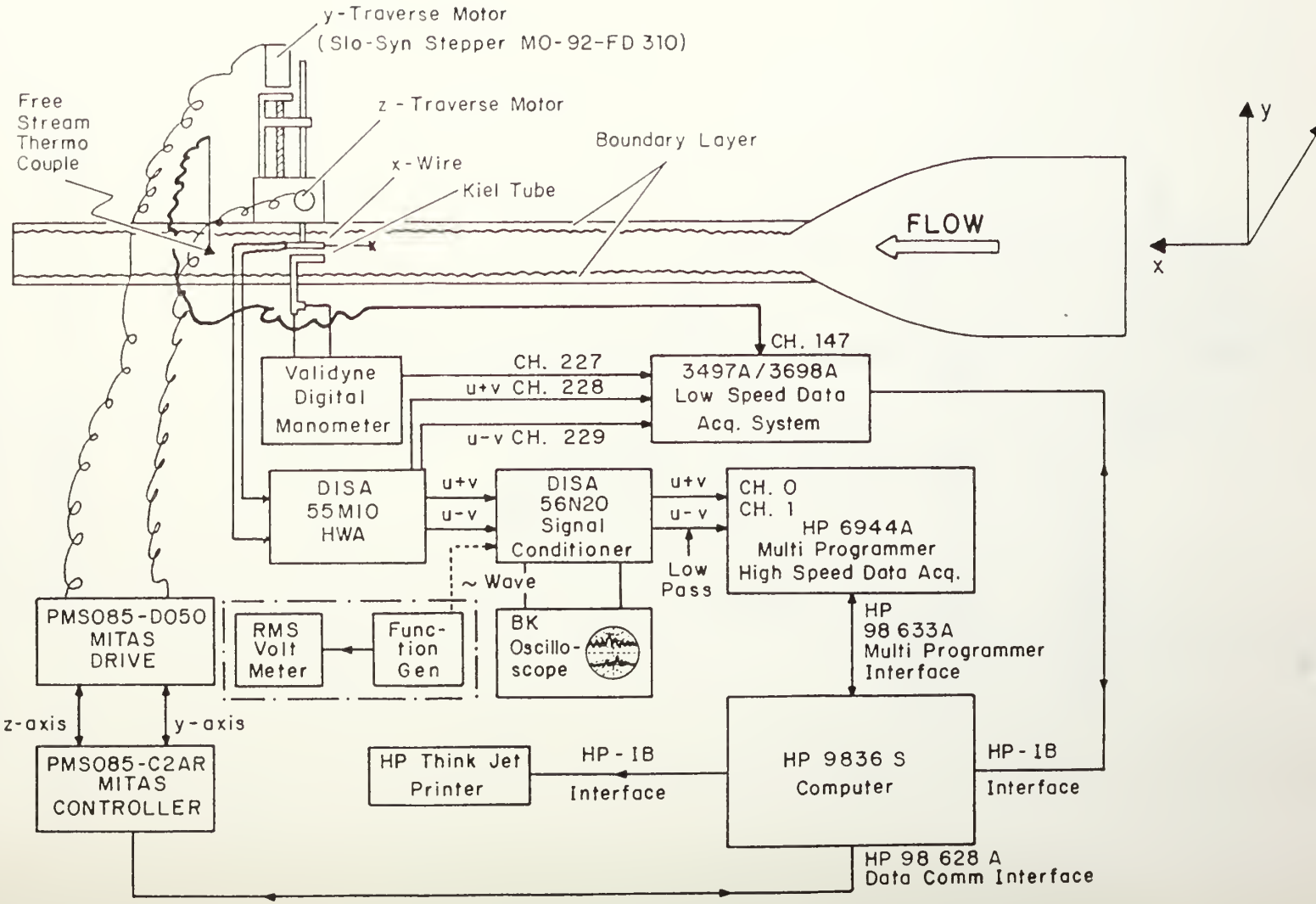

Figure 5. Data Acquisition System

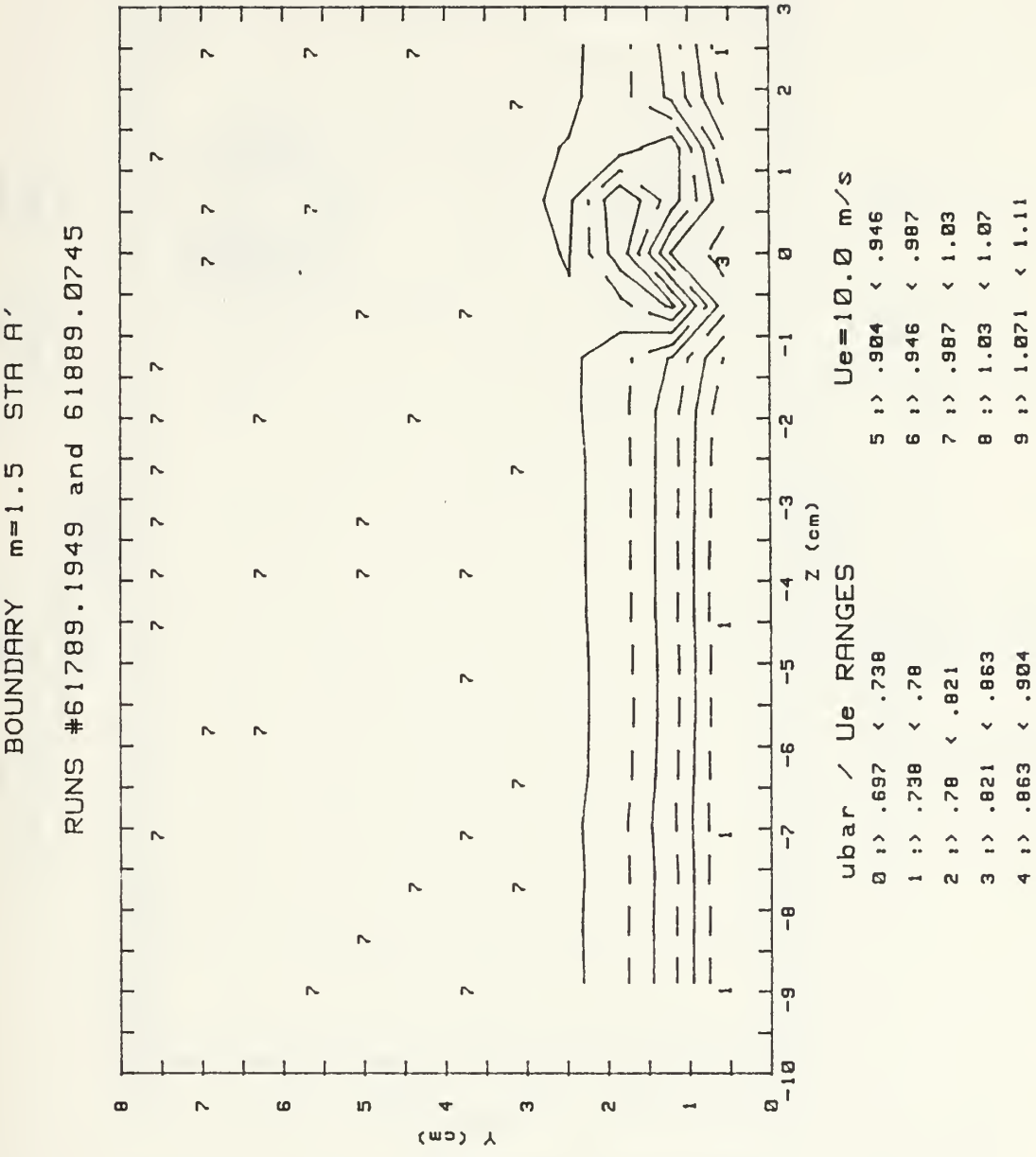

Figure 6. $\overline{u}$ (Boundary Layer, Station A', m = 1.5, Δ = 0.25)

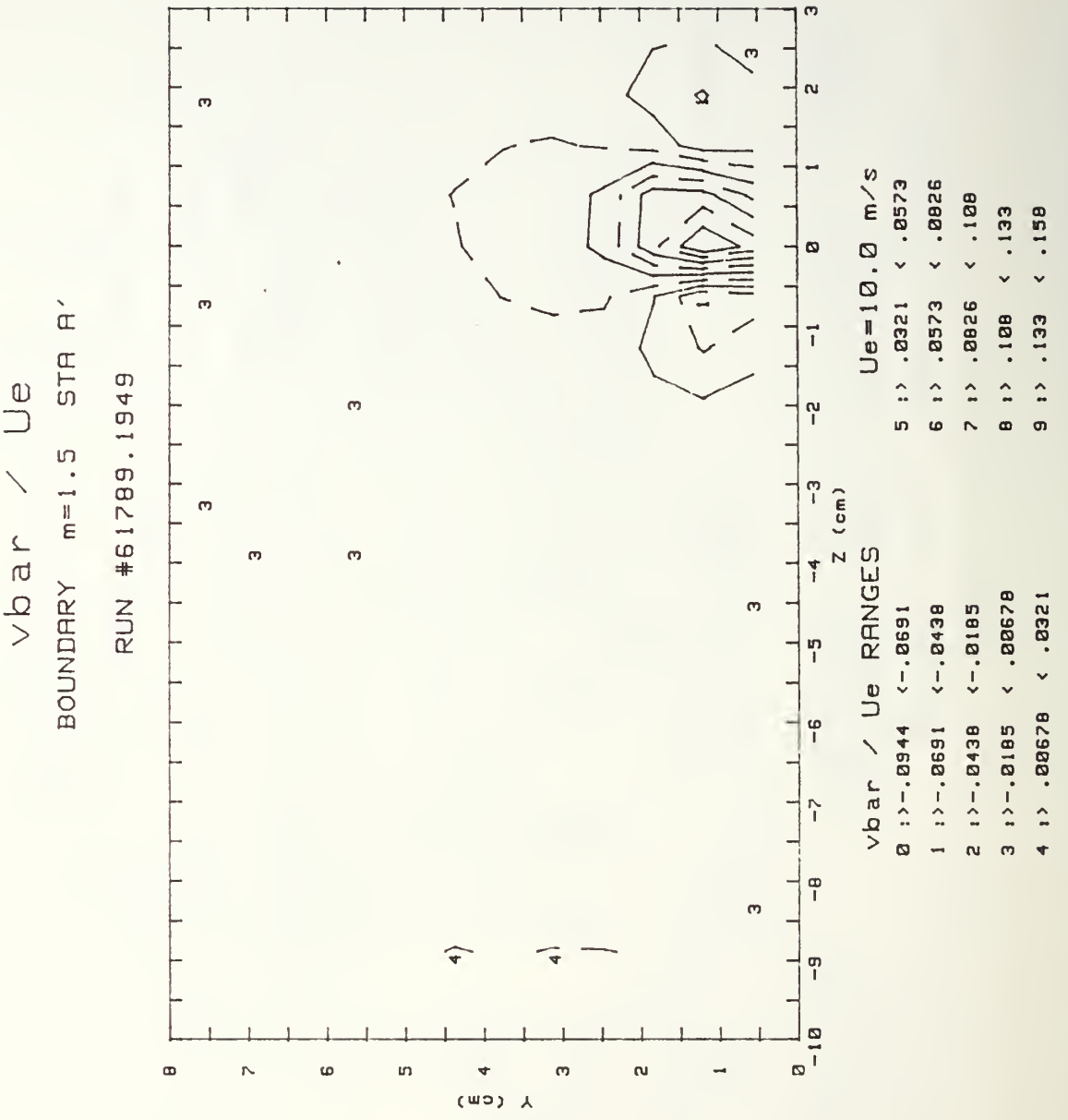

Figure 7. $\overline{v}$ (Boundary Layer, Station A', m = 1.5, Δ = 0.25)

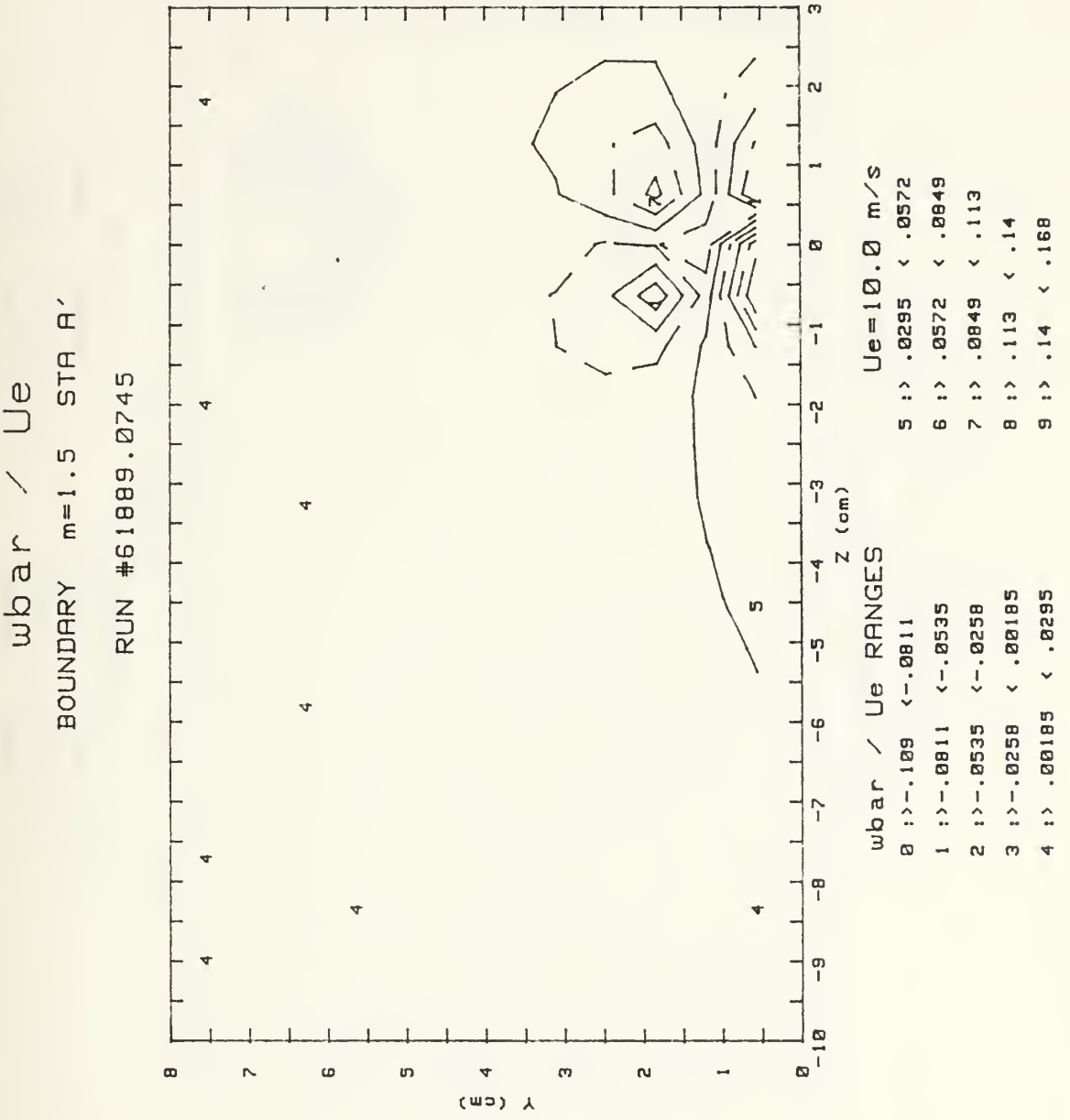

Figure 8. $\overline{w}$ (Boundary Layer, Station A', m = 1.5, Δ = 0.25)

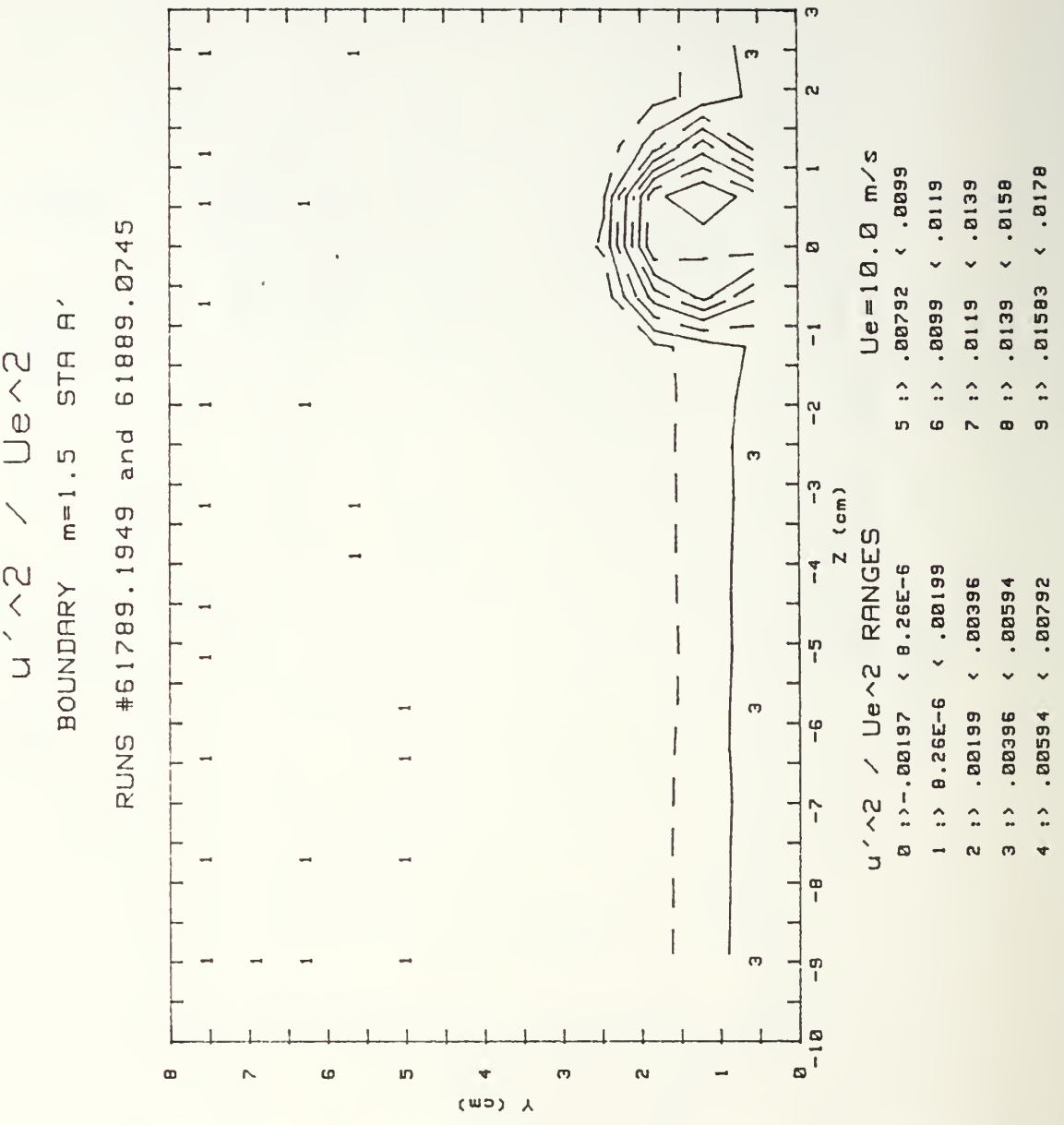

Figure 9. $\overline{u'^2}$ (Boundary Layer, Station A', m = 1.5, Δ = 0.25)

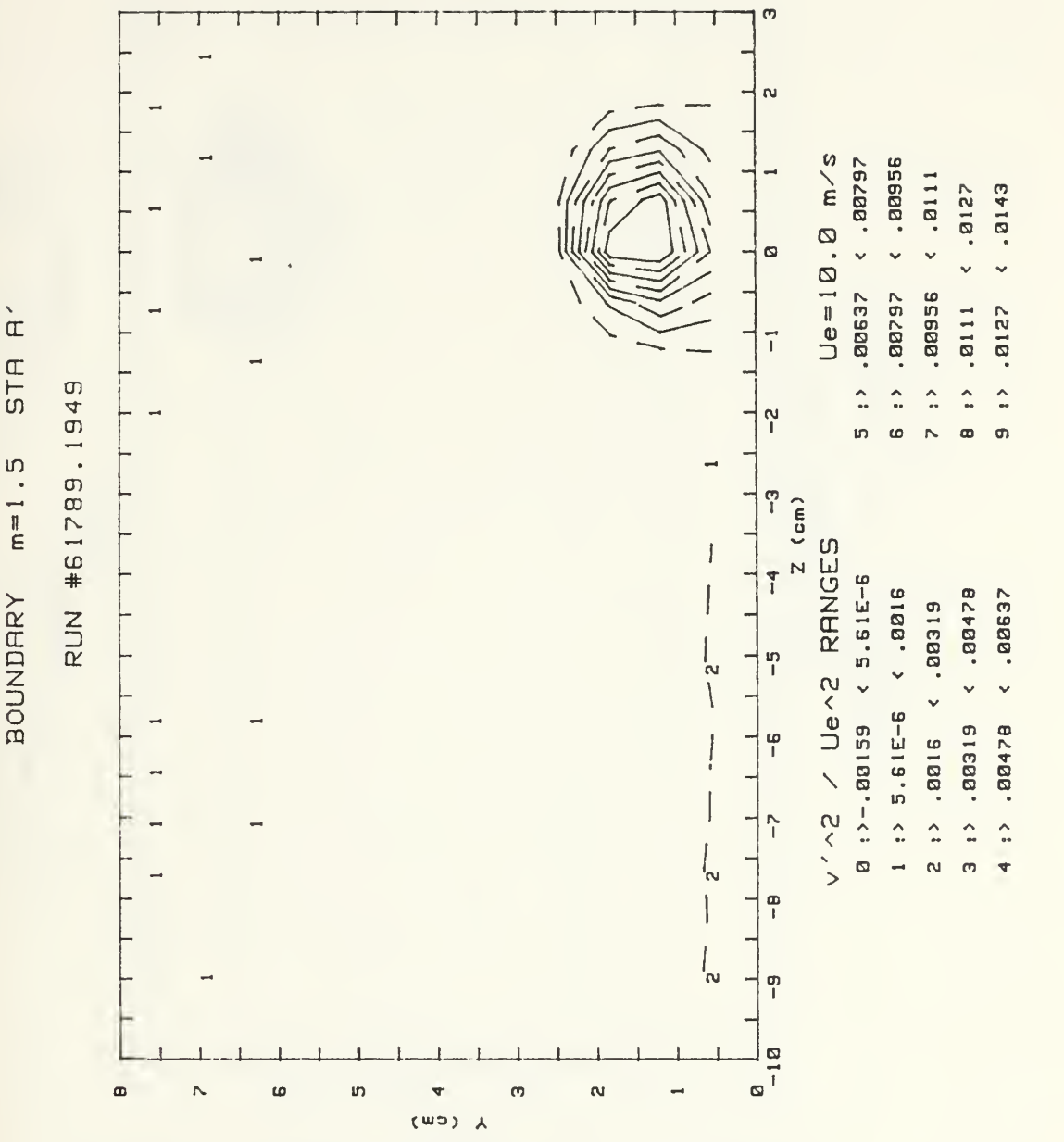

Figure 10. $\overline{v'^2}$ (Boundary Layer, Station A', m = 1.5, Δ= 0.25)

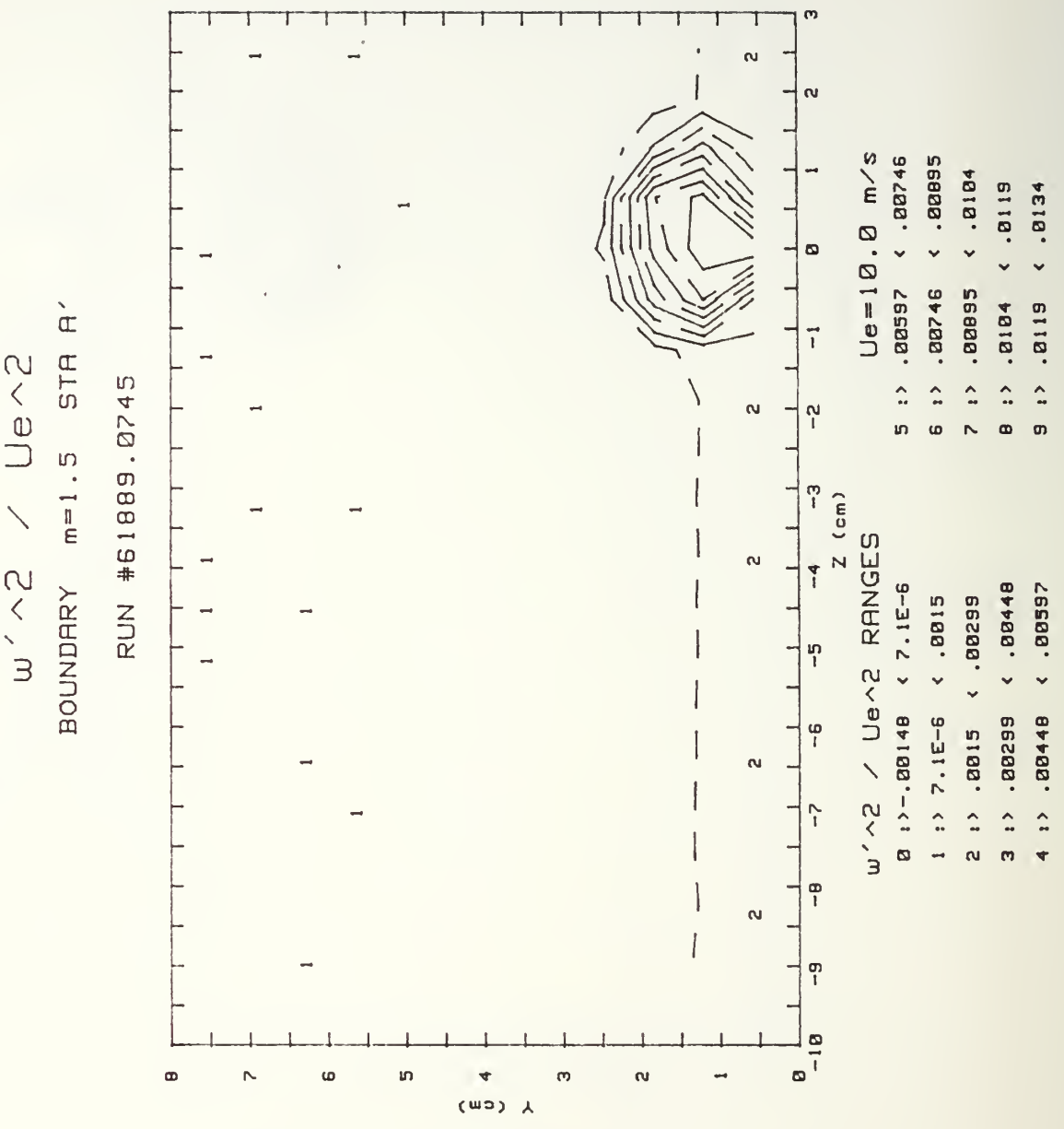

Figure 11. $\overline{w'^2}$ (Boundary Layer, Station A', m = 1.5, Δ = 0.25)

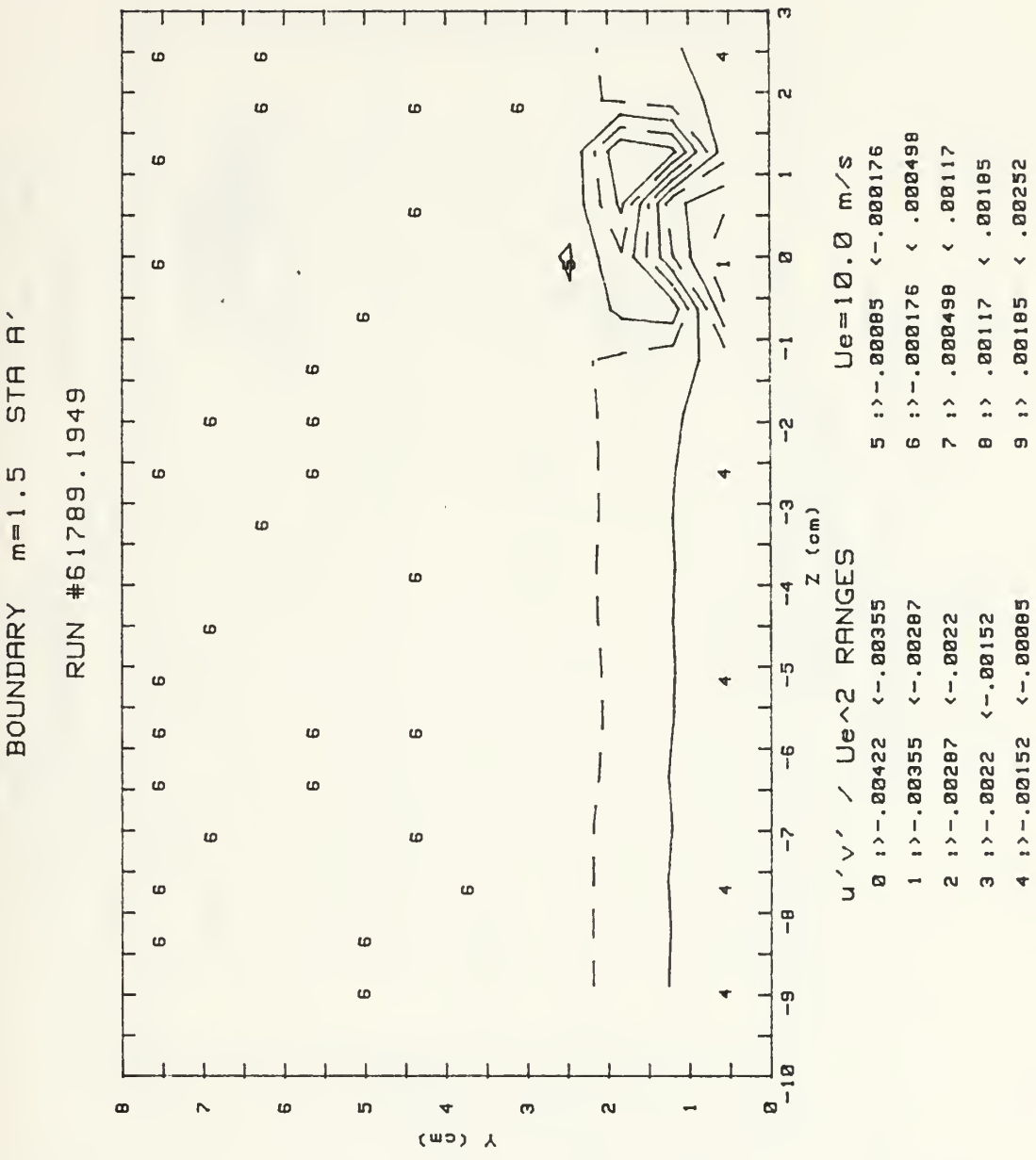

Figure 12. $\overline{u'v'}$ (Boundary Layer, Station A', m = 1.5, Δ= 0.25)

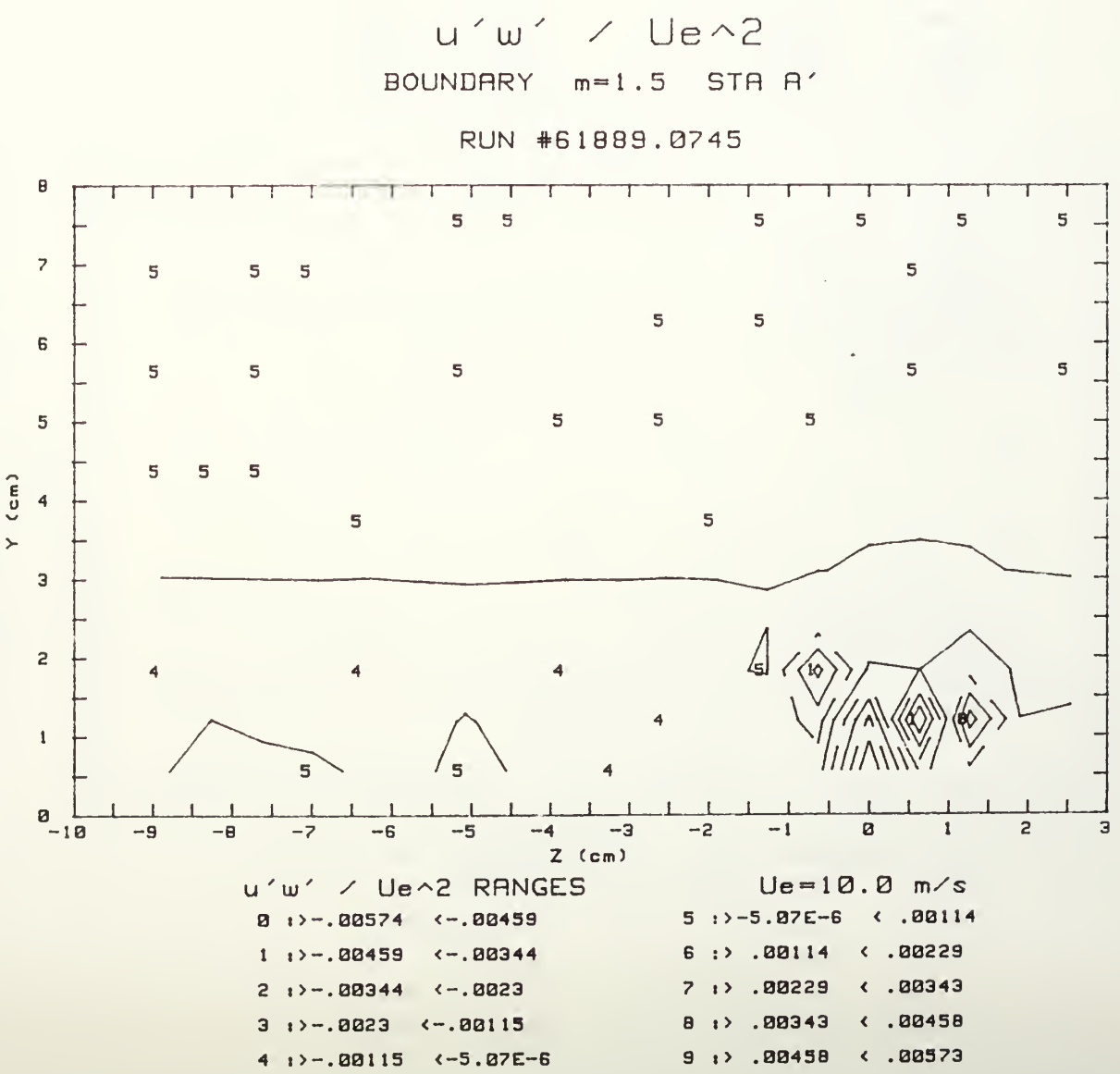

Figure 13. $\overline{u'w'}$ (Boundary Layer, Station A', m = 1.5, Δ= 0.25)

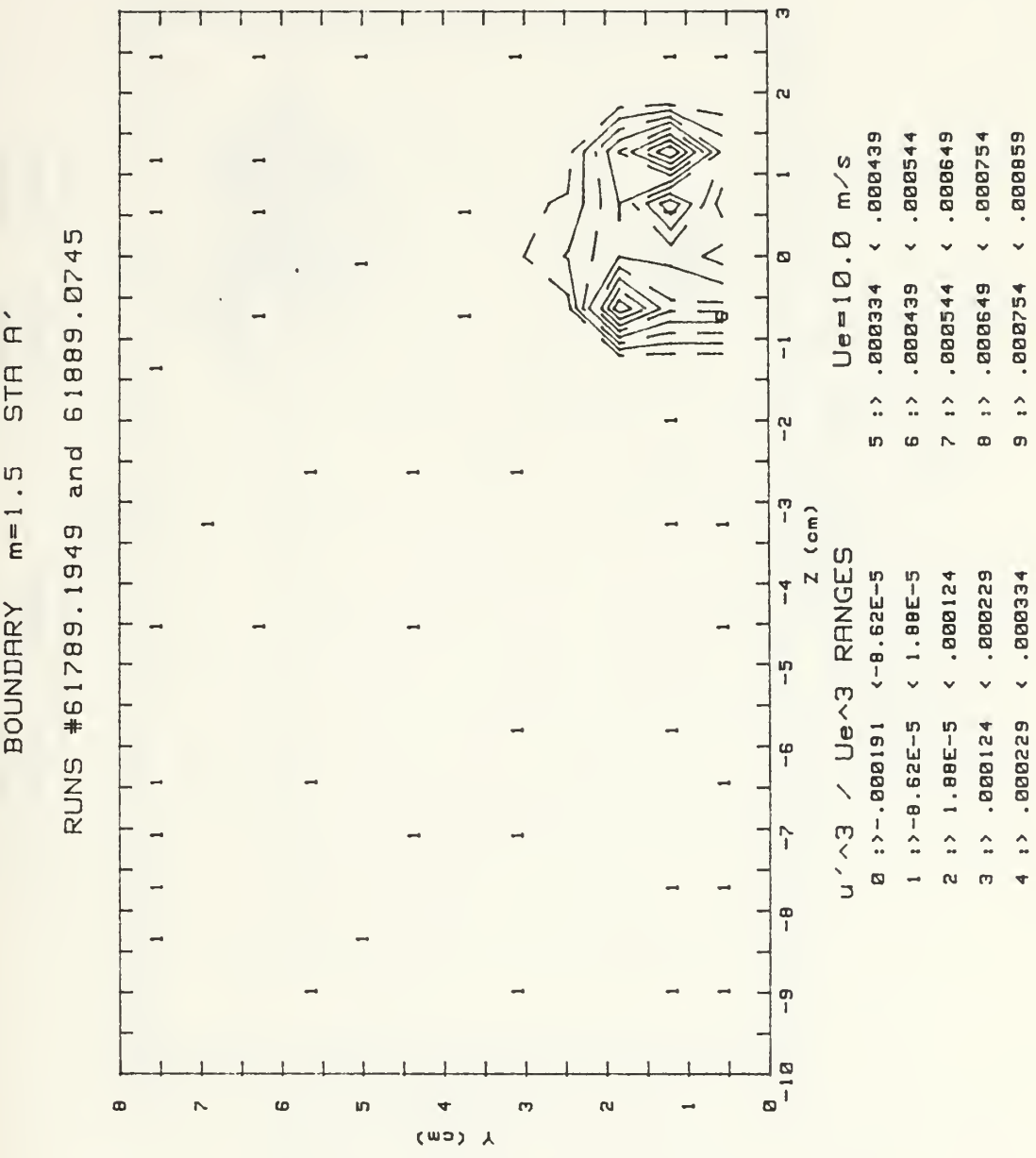

Figure 14. $\overline{u'^3}$ (Boundary Layer, Station A', m = 1.5, Δ= 0.25)

Figure 15. $\overline{v'^3}$ (Boundary Layer, Station A', m = 1.5, Δ= 0.25)

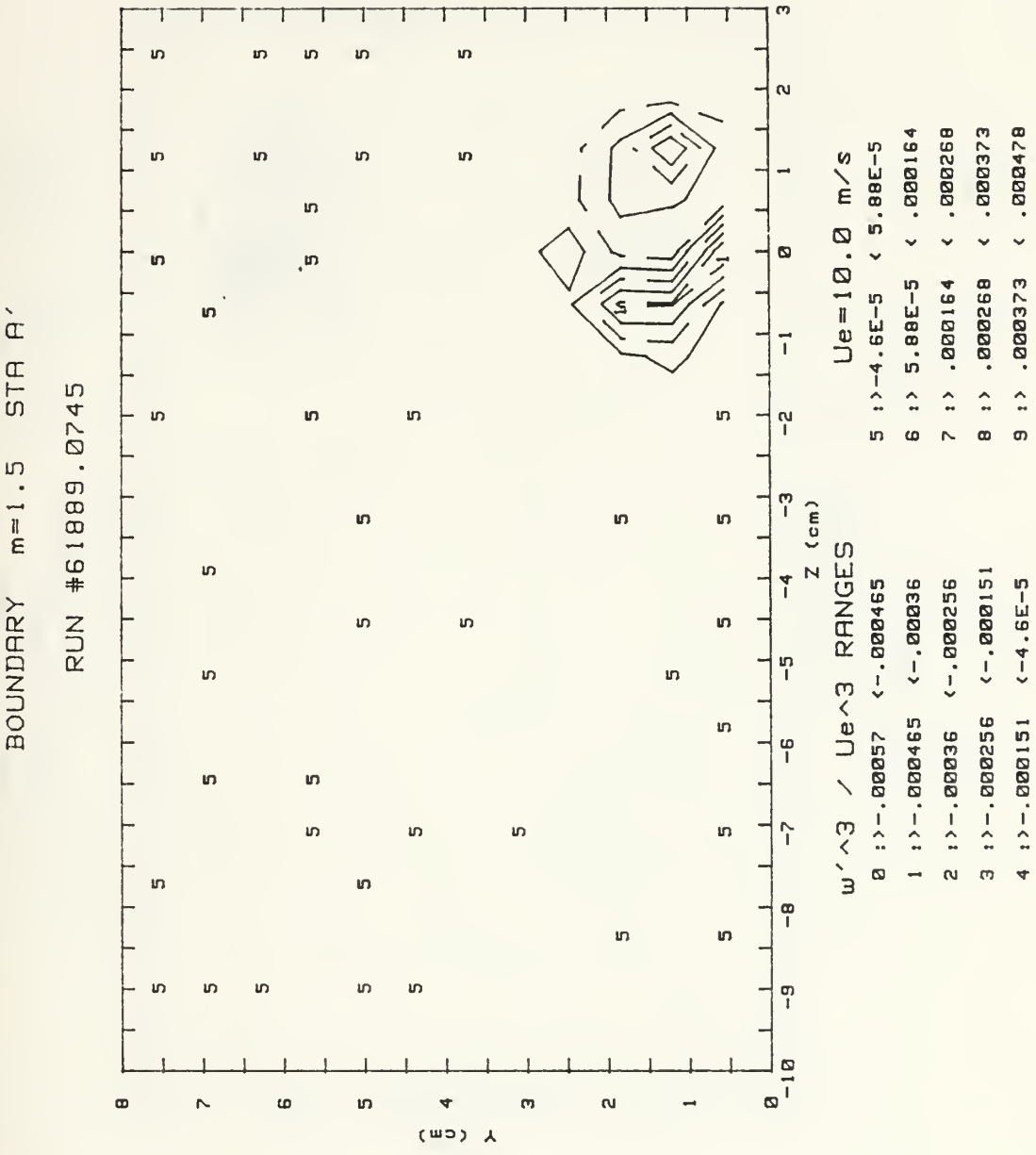

Figure 16. $\overline{w'^3}$ (Boundary Layer, Station A', m = 1.5, Δ = 0.25)

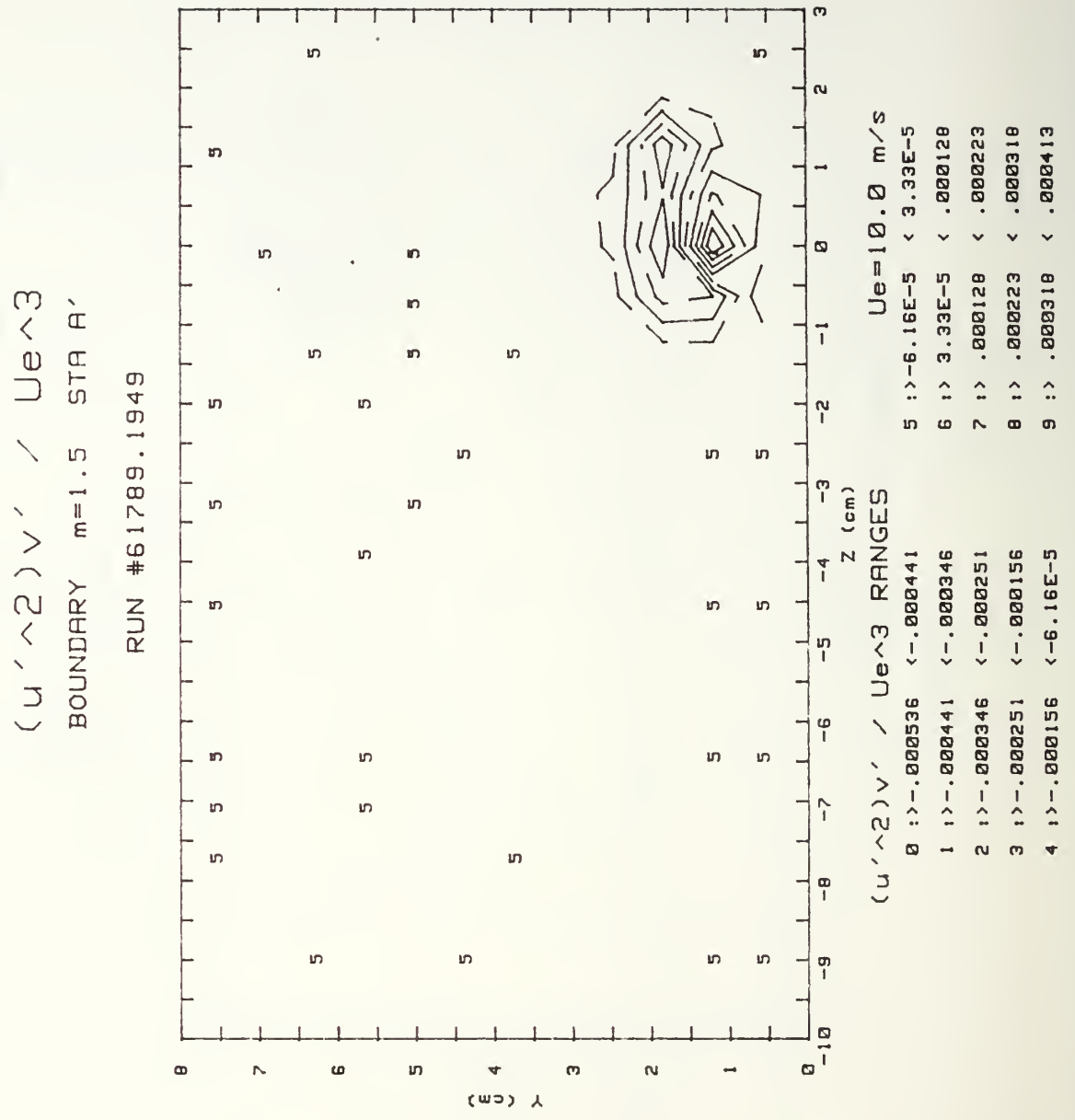

Figure 17. $\overline{u'^2v'}$ (Boundary Layer, Station A', m = 1.5, Δ= 0.25)

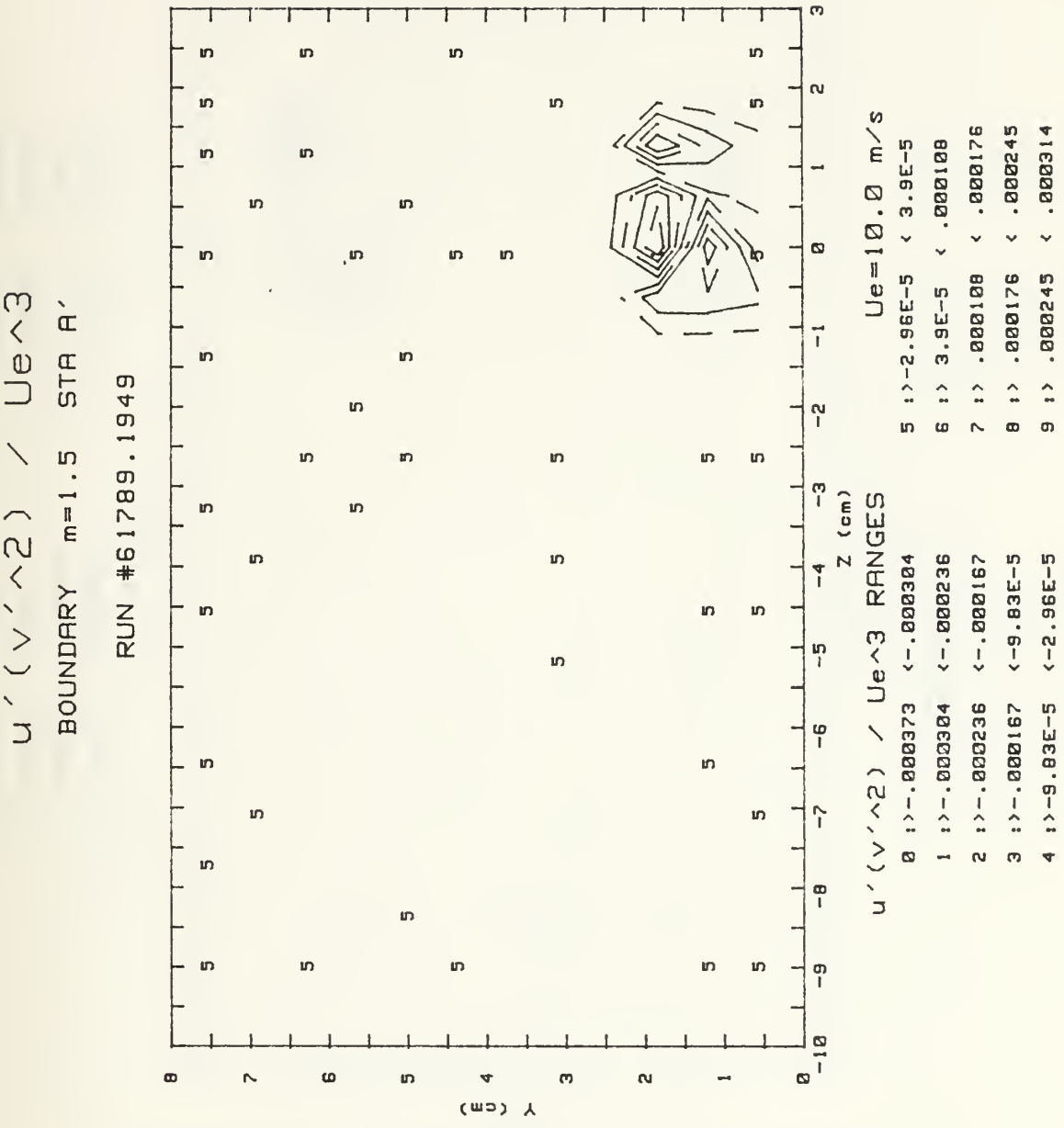

Figure 18. $\overline{u'v'^2}$ (Boundary Layer, Station A', m = 1.5, Δ= 0.25)

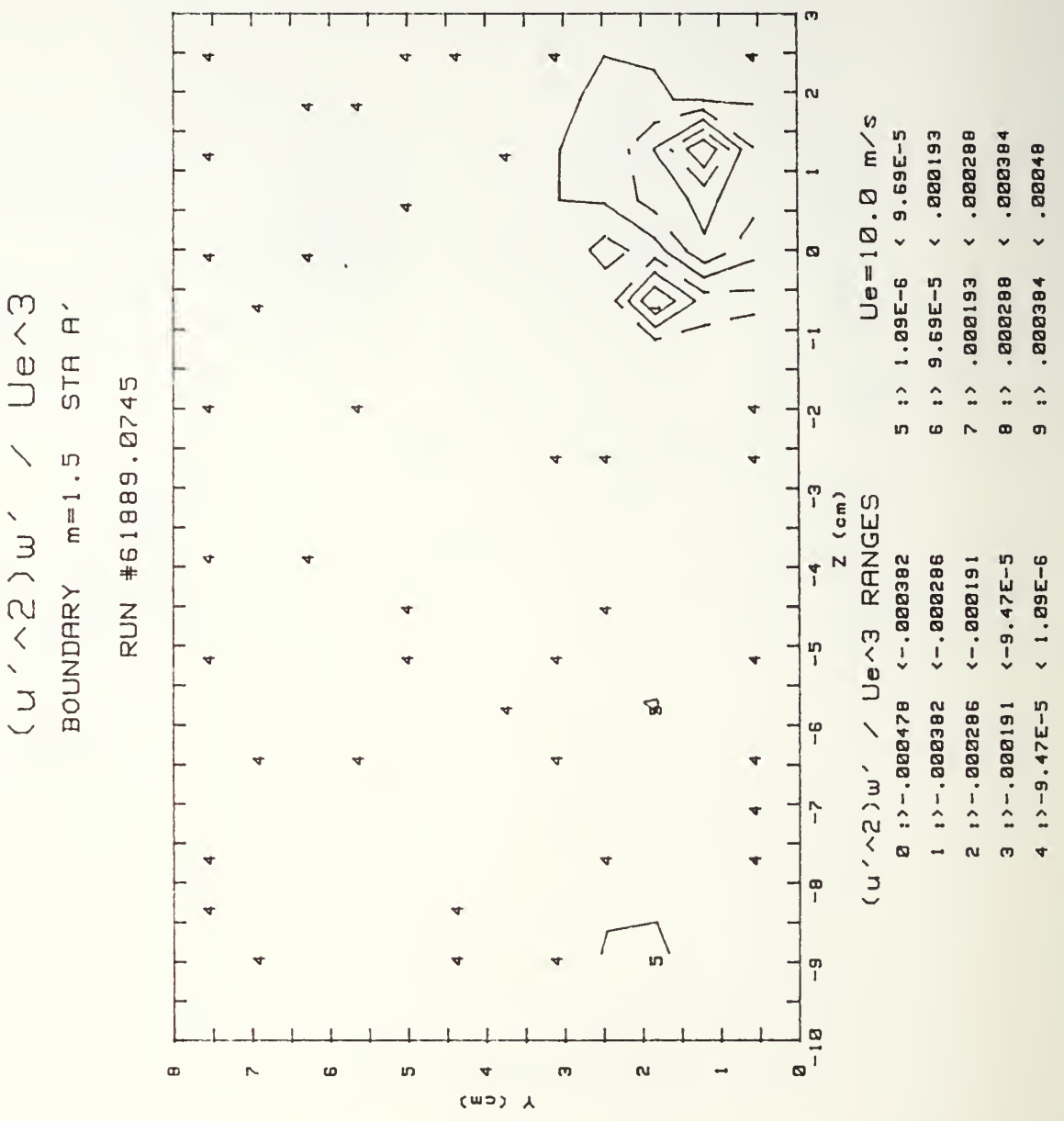

Figure 19. $\overline{u'^2w'}$ (Boundary Layer, Station A', m = 1.5, Δ= 0.25)

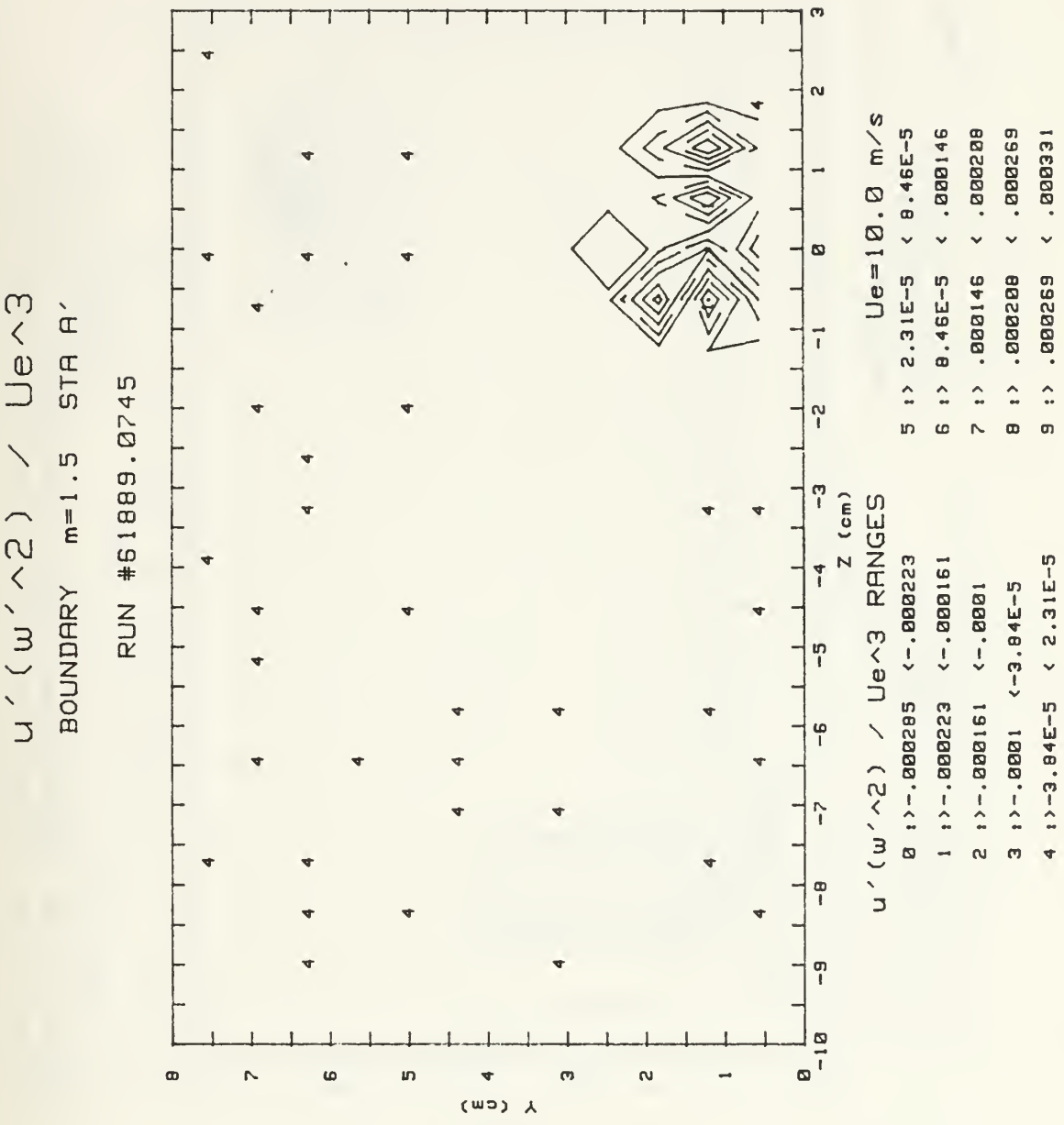

Figure 20. $\overline{u'w'^2}$ (Boundary Layer, Station A', m = 1.5, Δ = 0.25)

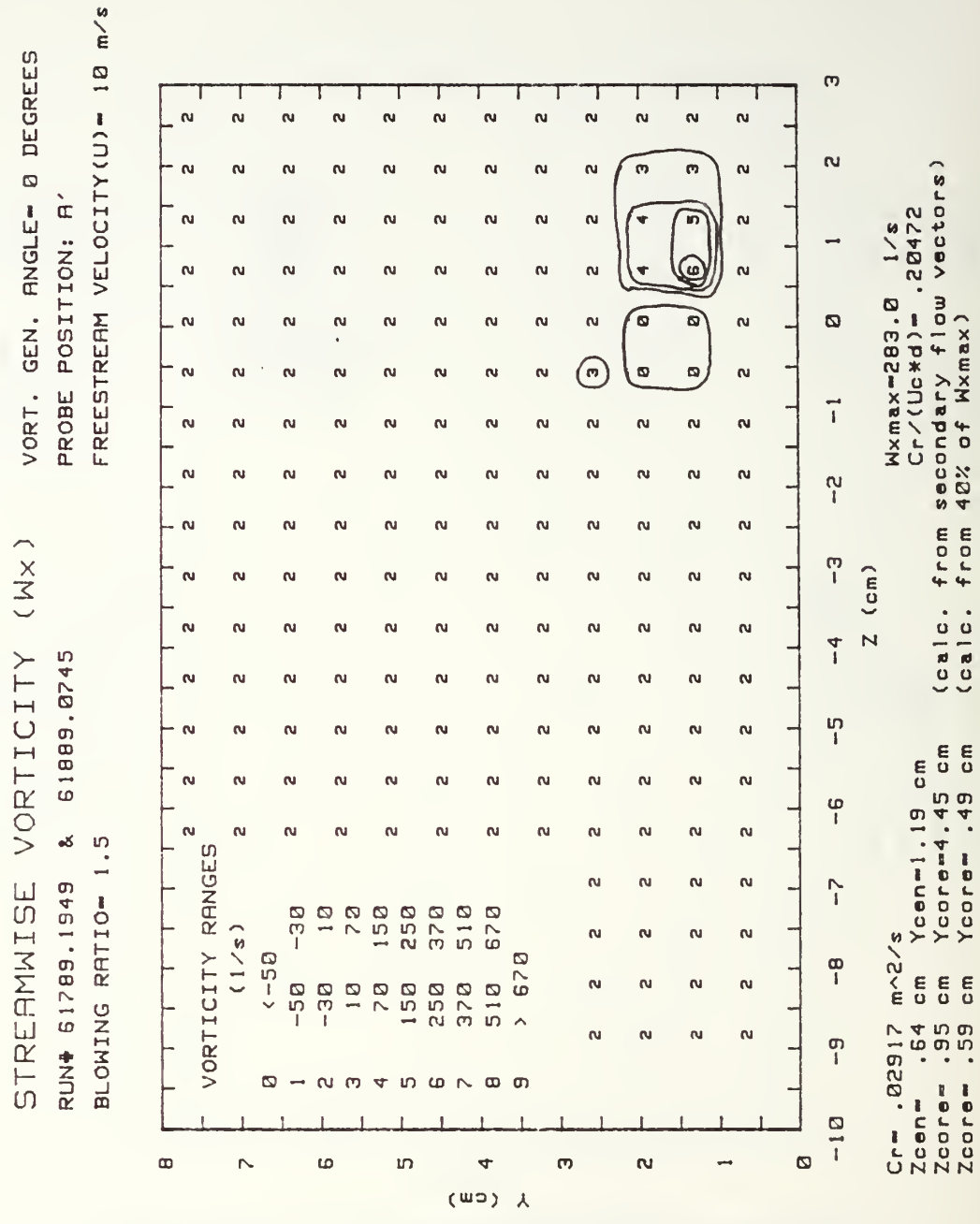

Figure 21. Streamwise Vorticity (Boundary Layer, Station A', m = 1.5, Δ = 0.25)

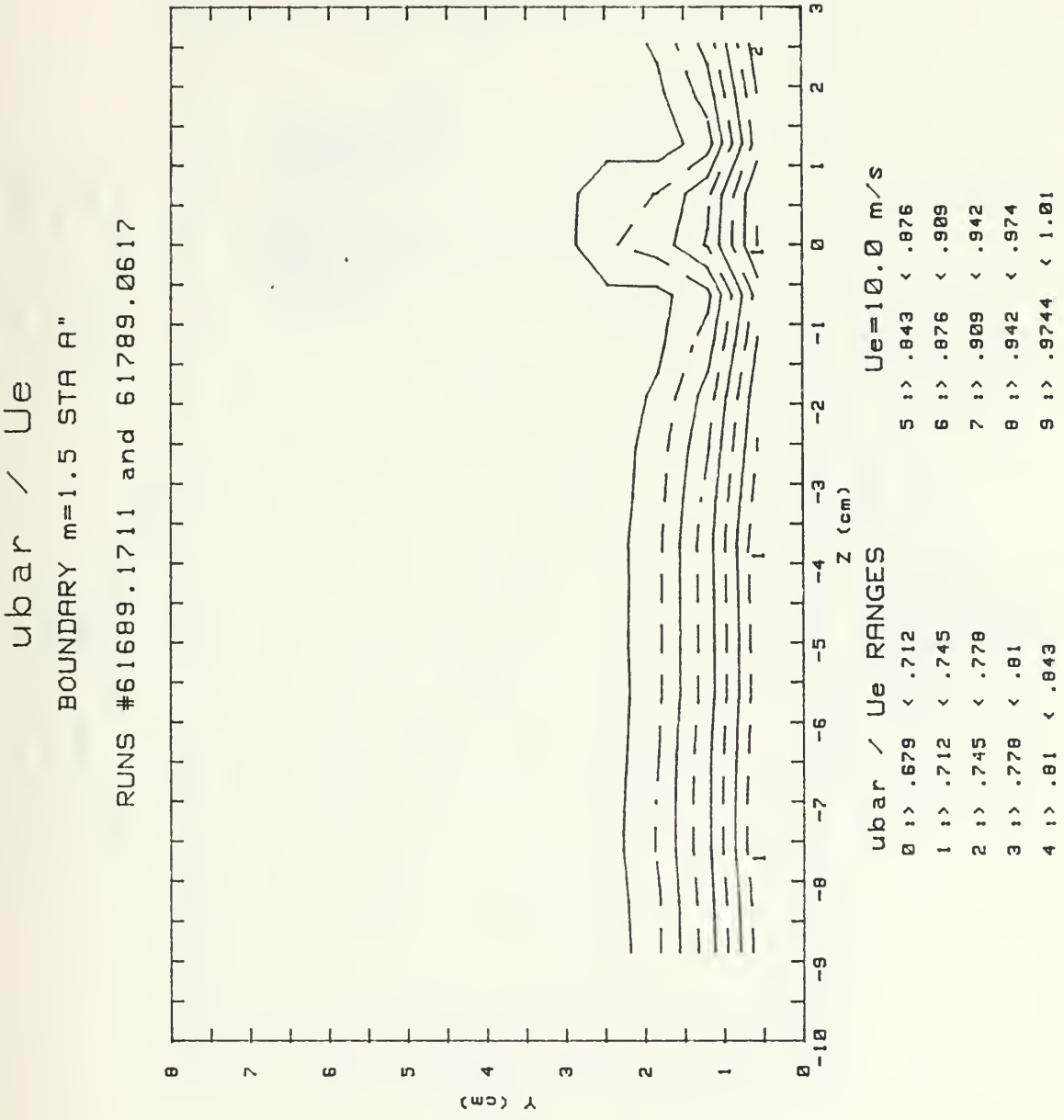

Figure 22. $\overline{u}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

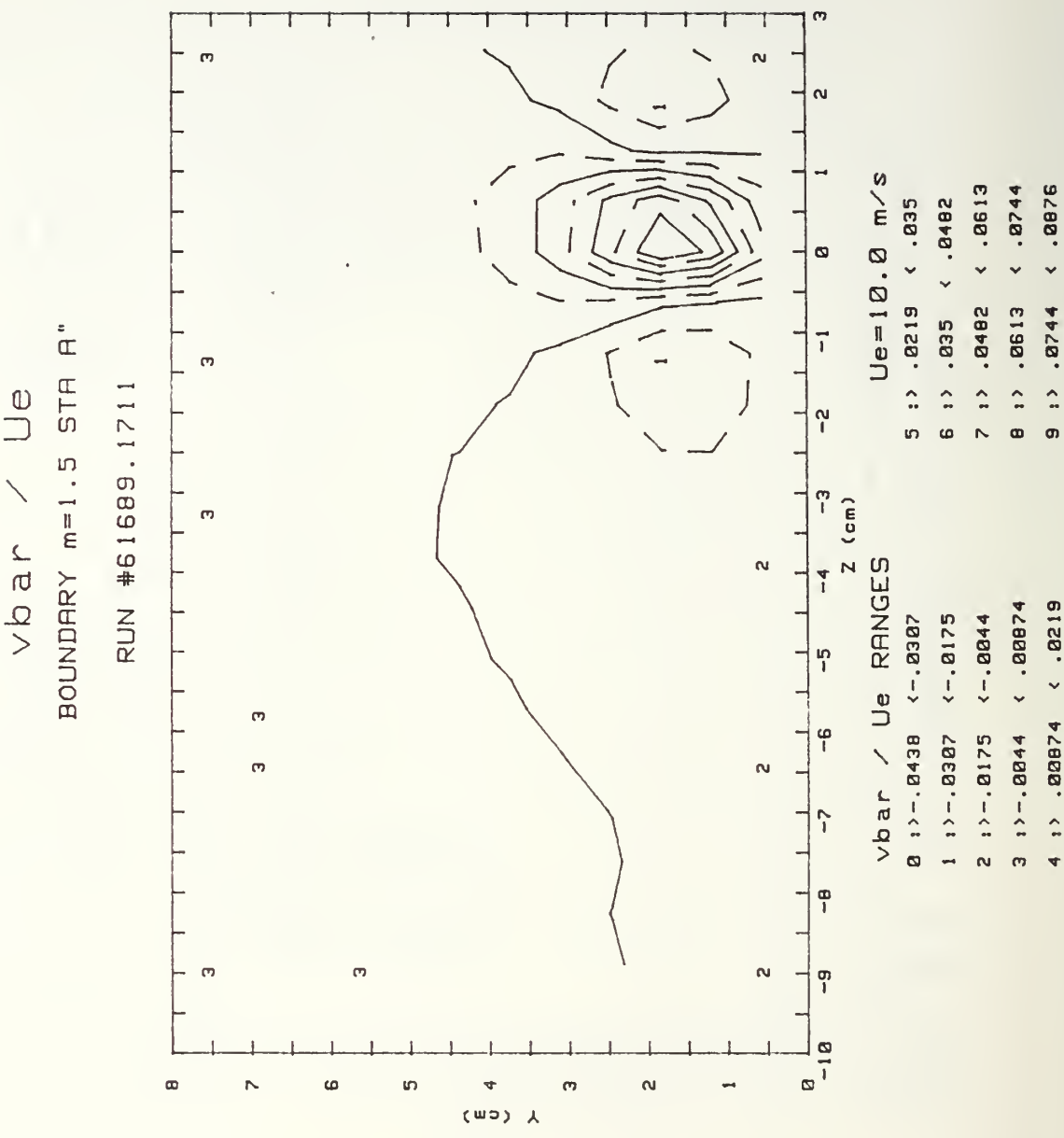

Figure 23. $\overline{v}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

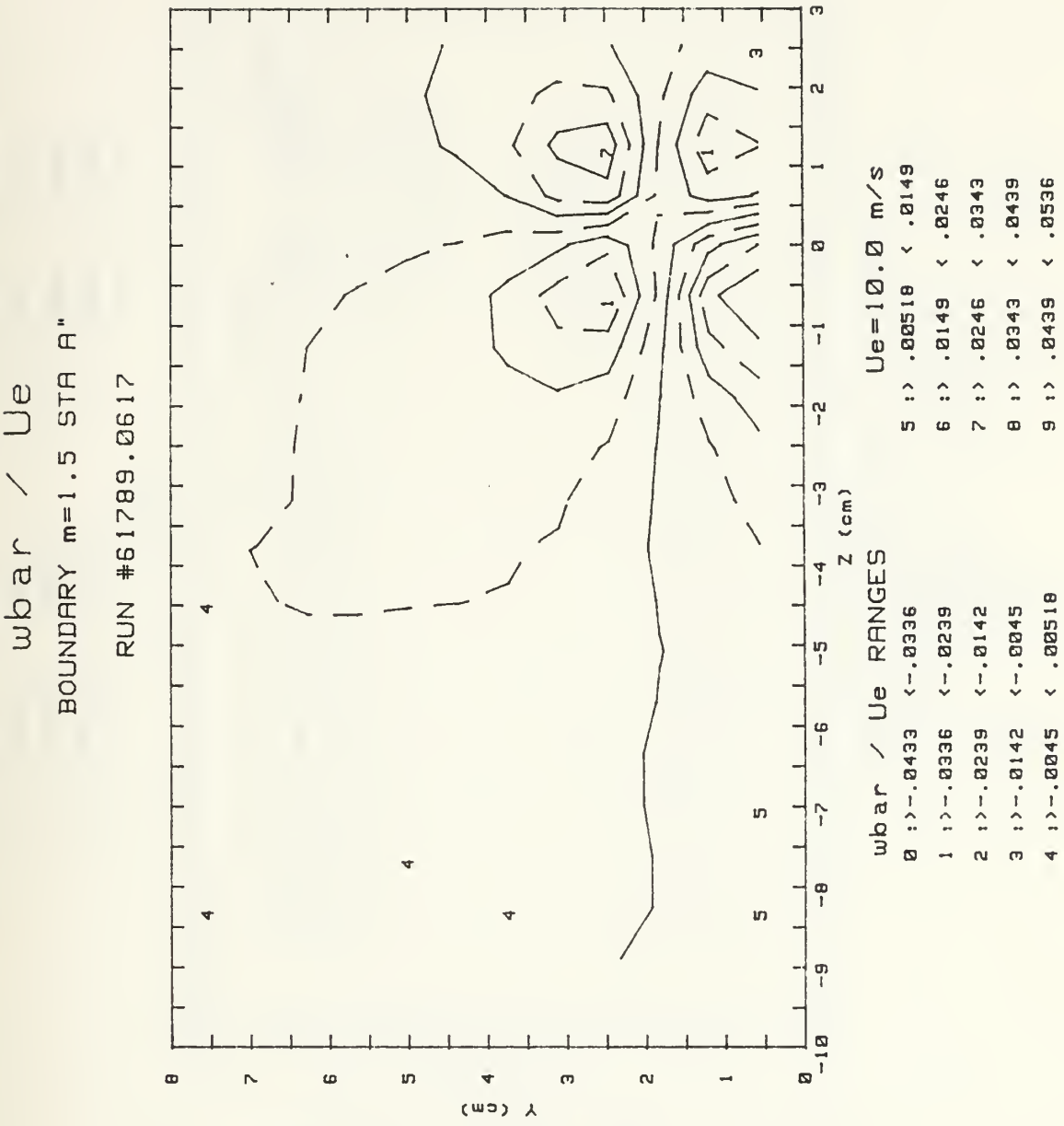

Figure 24. $\overline{w}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

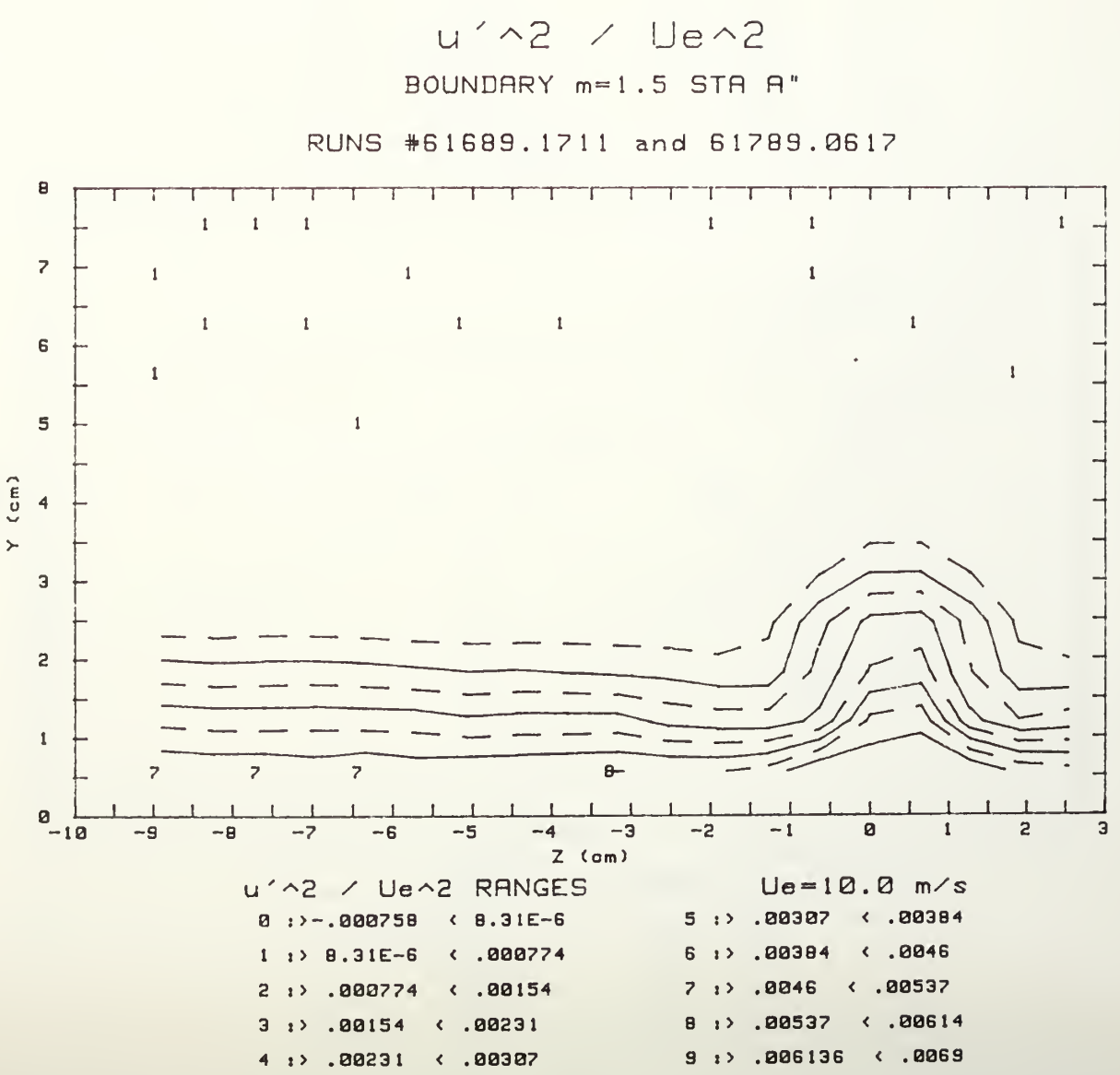

Figure 25. $\overline{u'^2}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

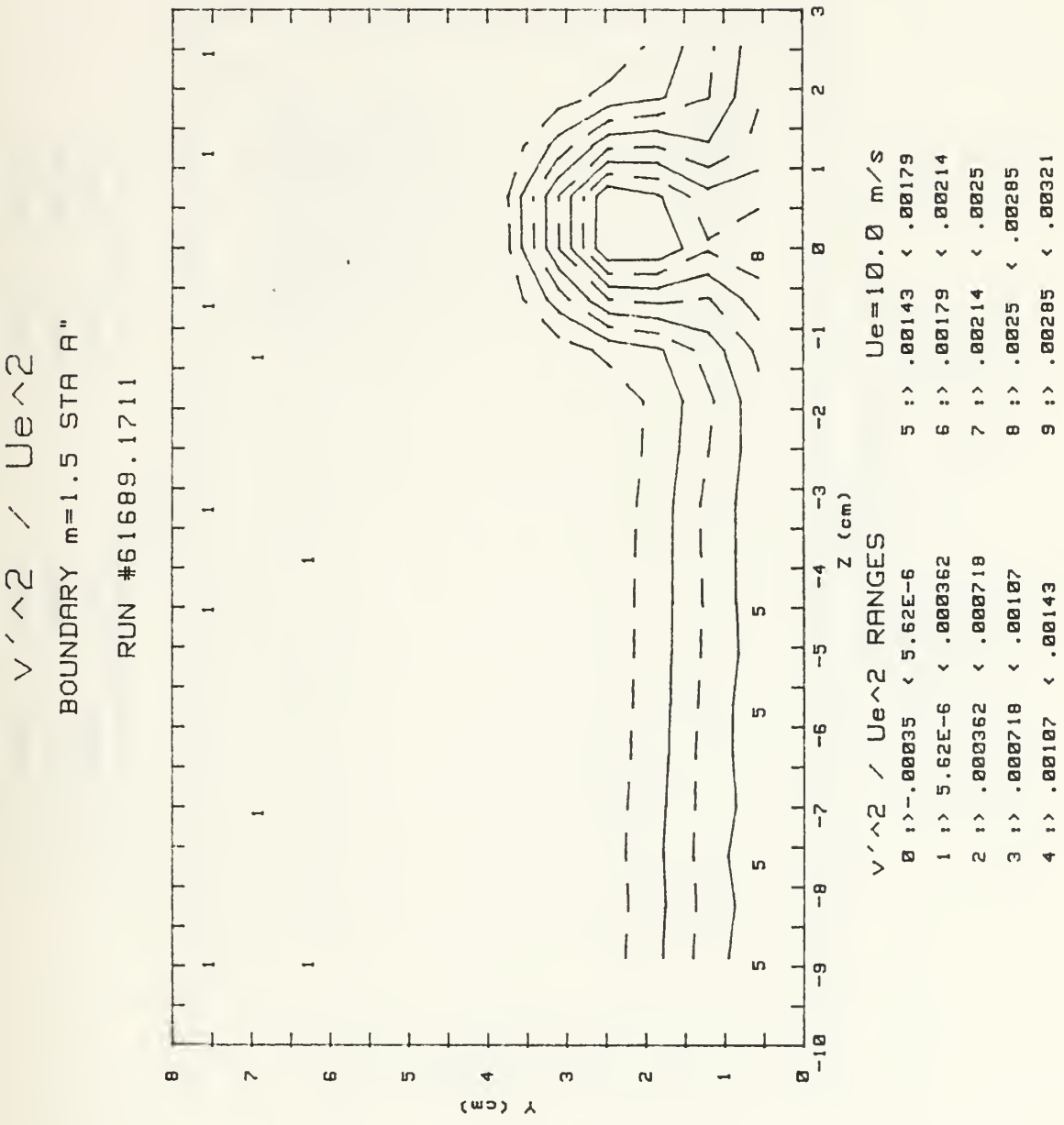

Figure 26. $\overline{v'^2}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

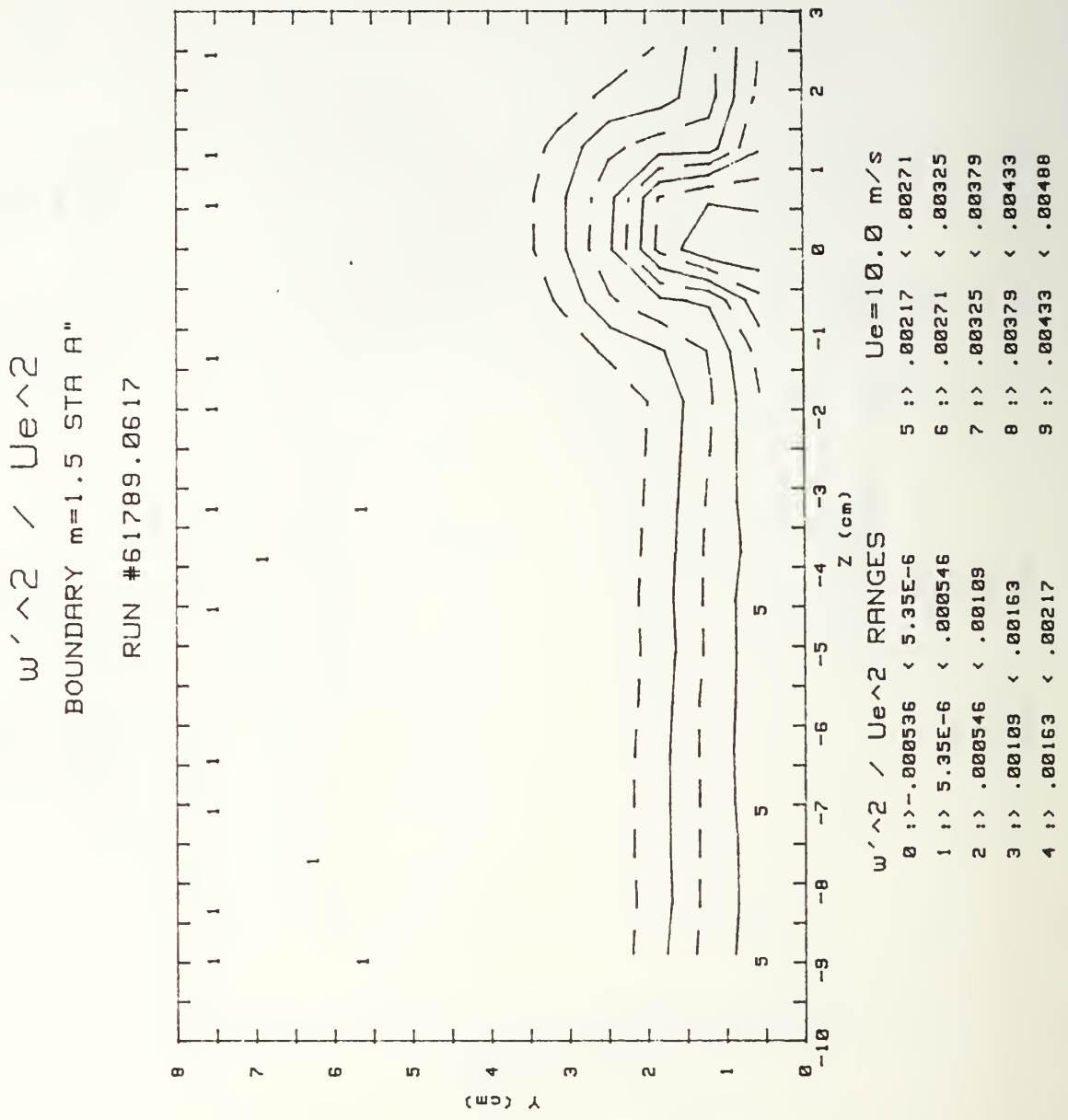

Figure 27. $\overline{w'^2}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

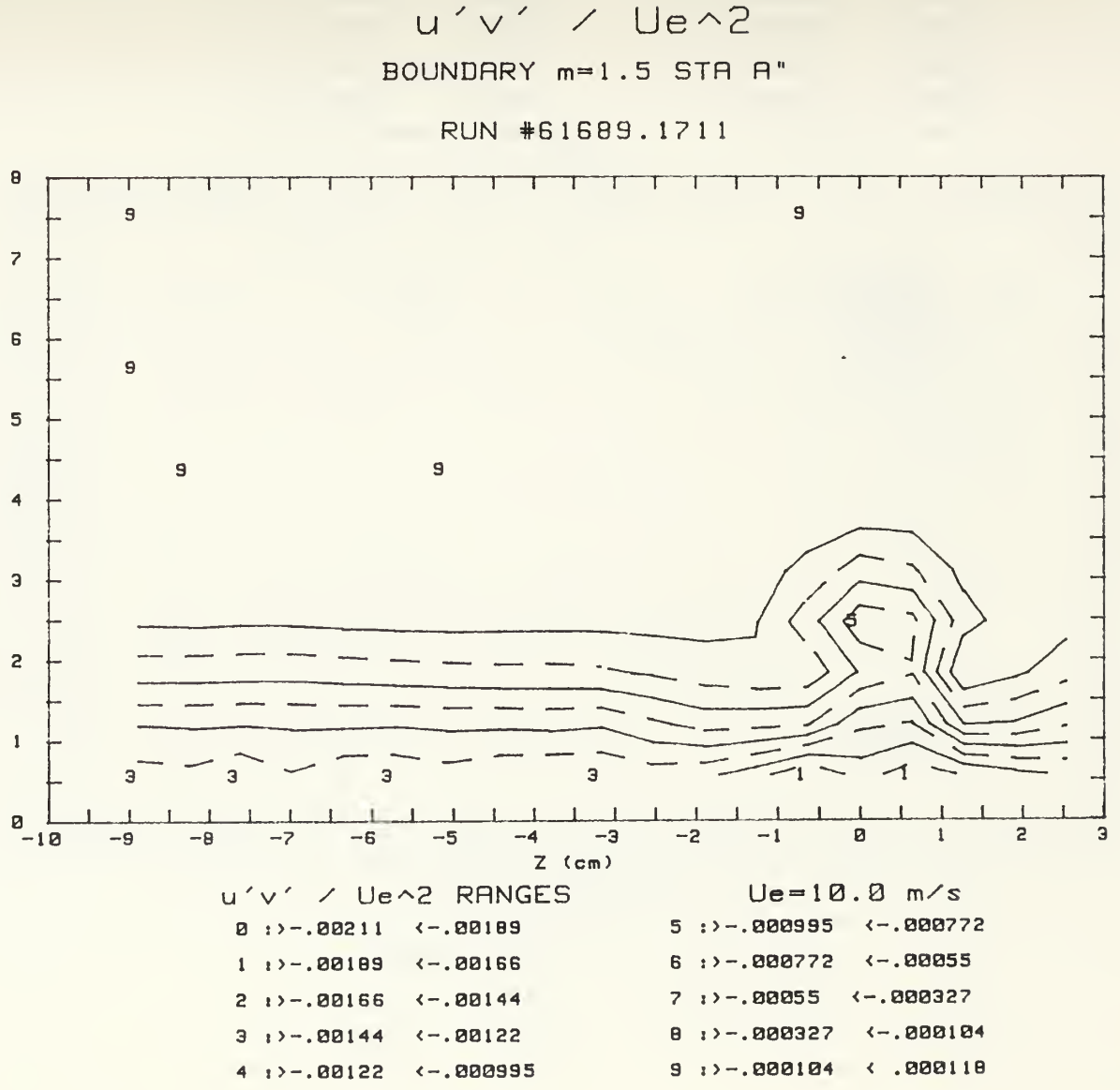

Figure 28. $\overline{u'v'}$ (Boundary layer, Station A'', m = 1.5, Δ = 0.25)

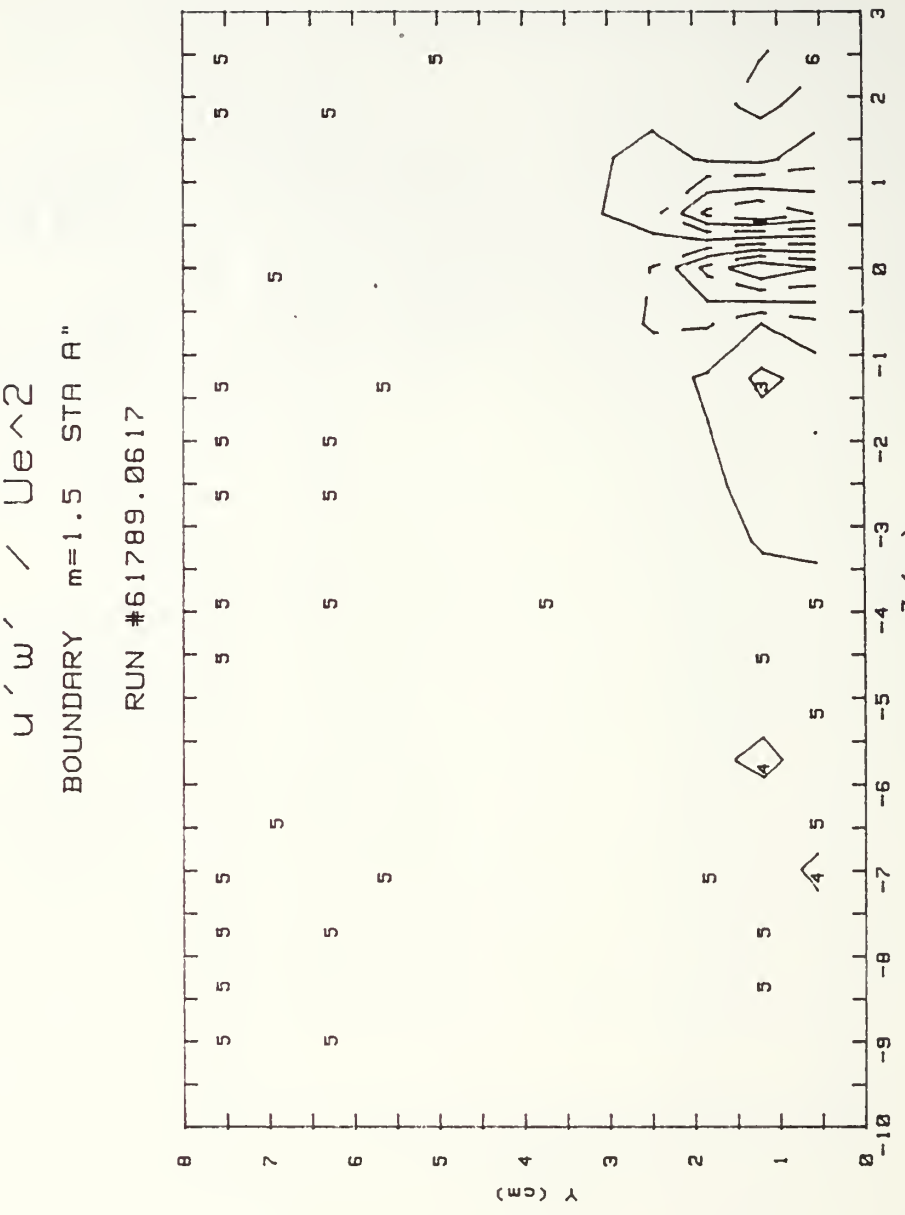

Figure 29. $\overline{u'w'}$ (Boundary Layer, Station A'', m = 1.5, Δ= 0.25)

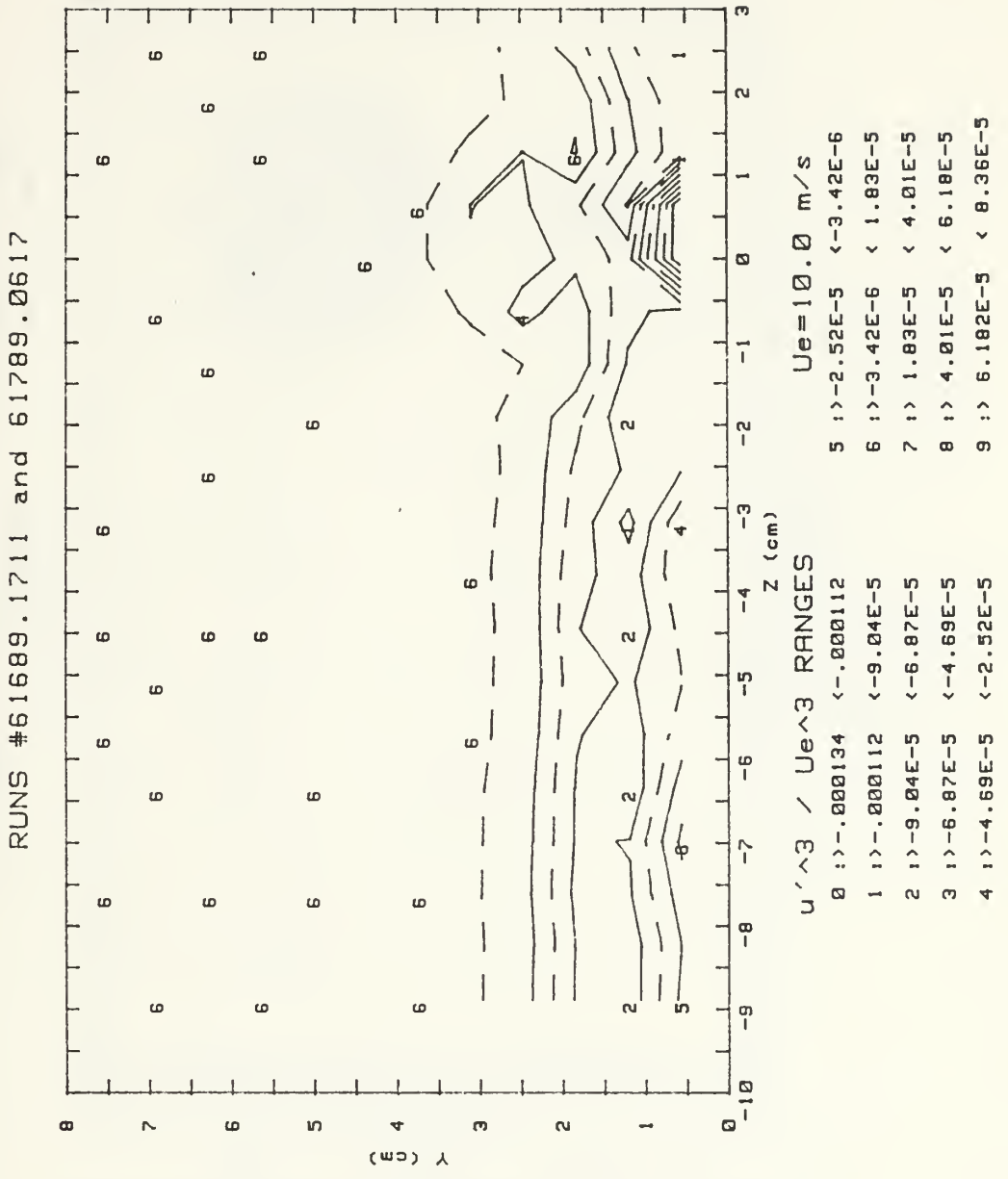

Figure 30. $\overline{u'^3}$ (Boundary Layer, Station A'', m = 1.5, Δ= 0.25)

Figure 31. $\overline{v'^3}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

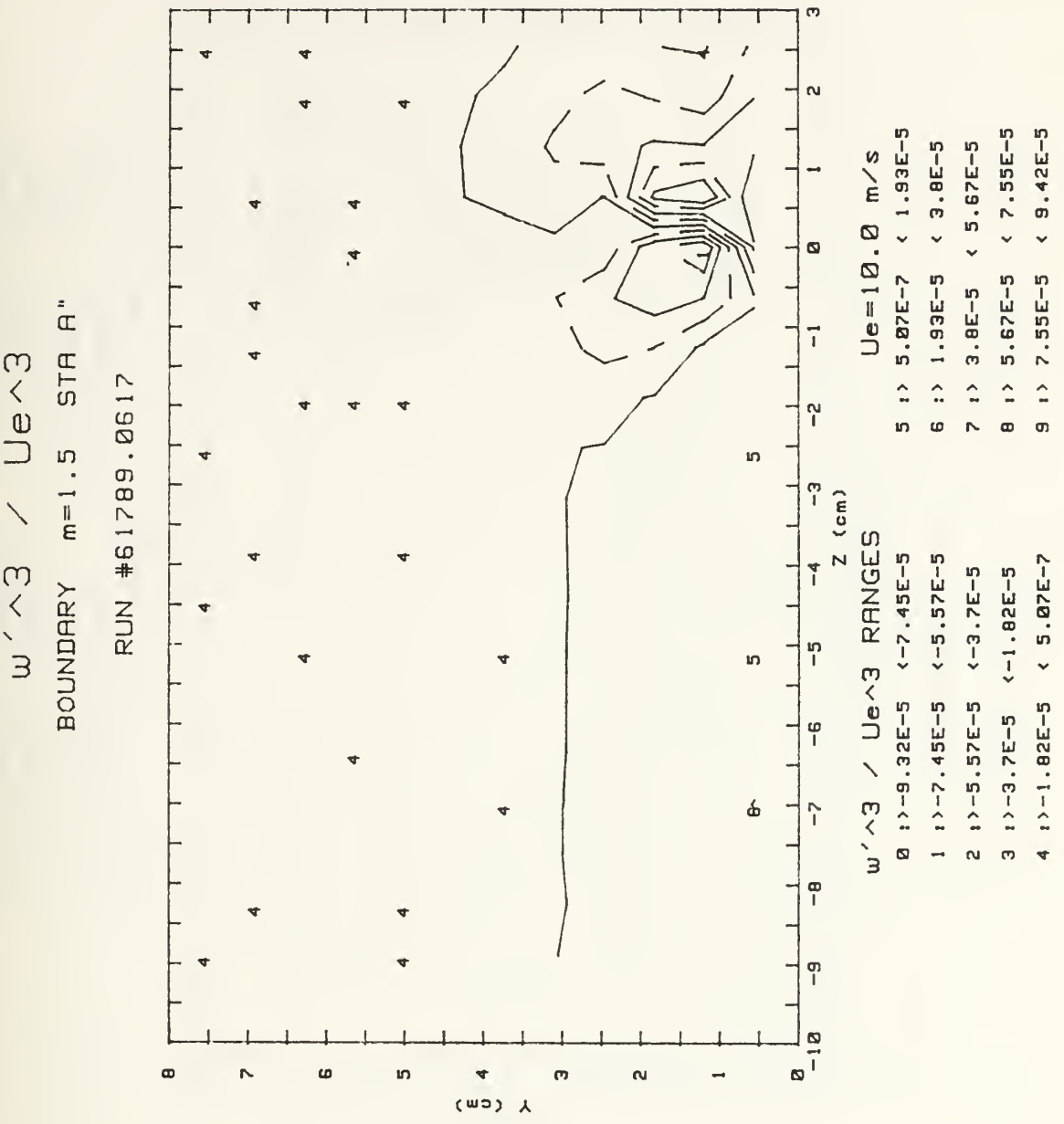

Figure 32. $\overline{w'^3}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

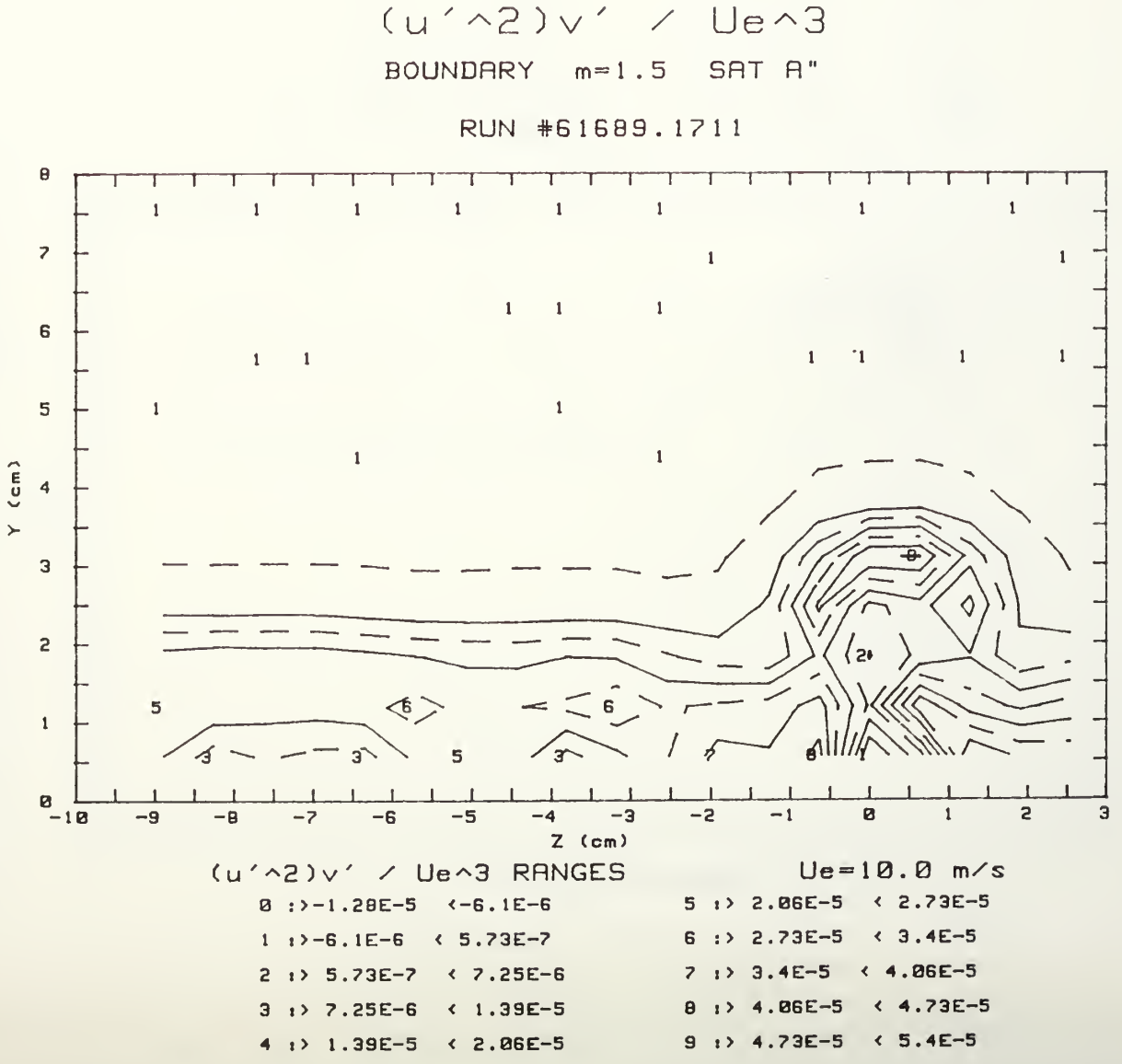

Figure 33. $\overline{u'^2v'}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

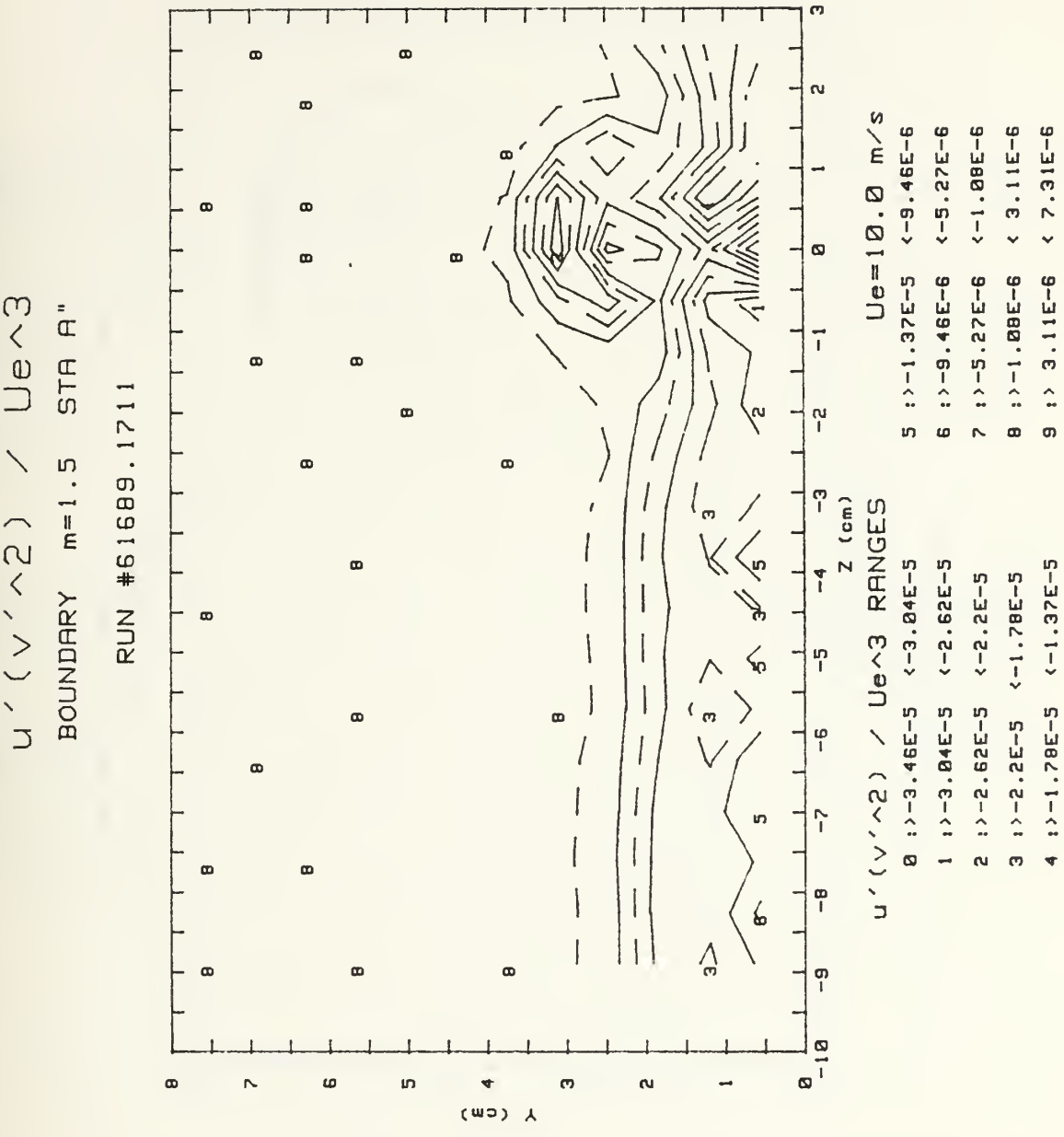

Figure 34. $\overline{u'v'^2}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

Figure 35. $\overline{u'^2w'}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

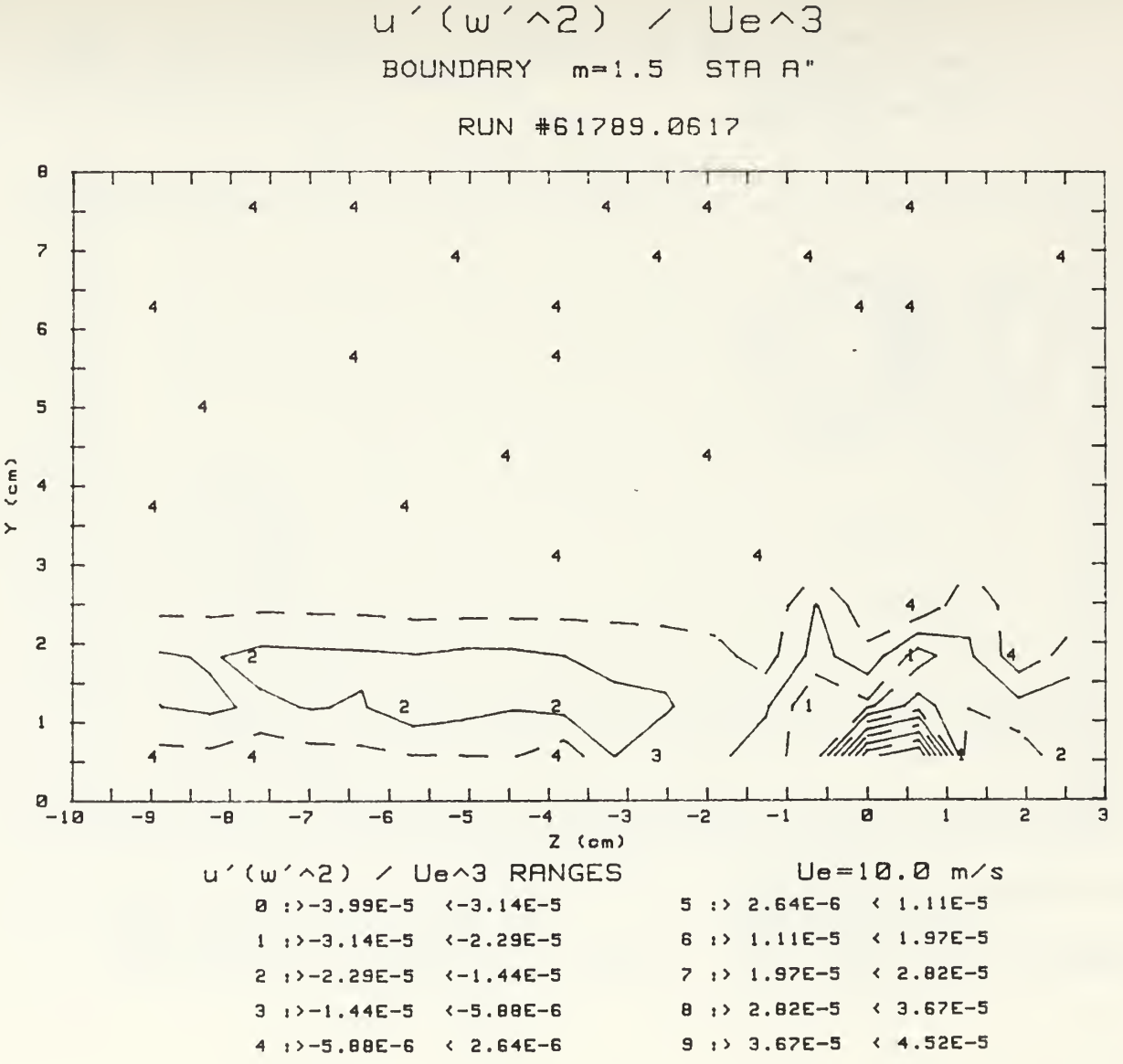

Figure 36. $\overline{u'w'^2}$ (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

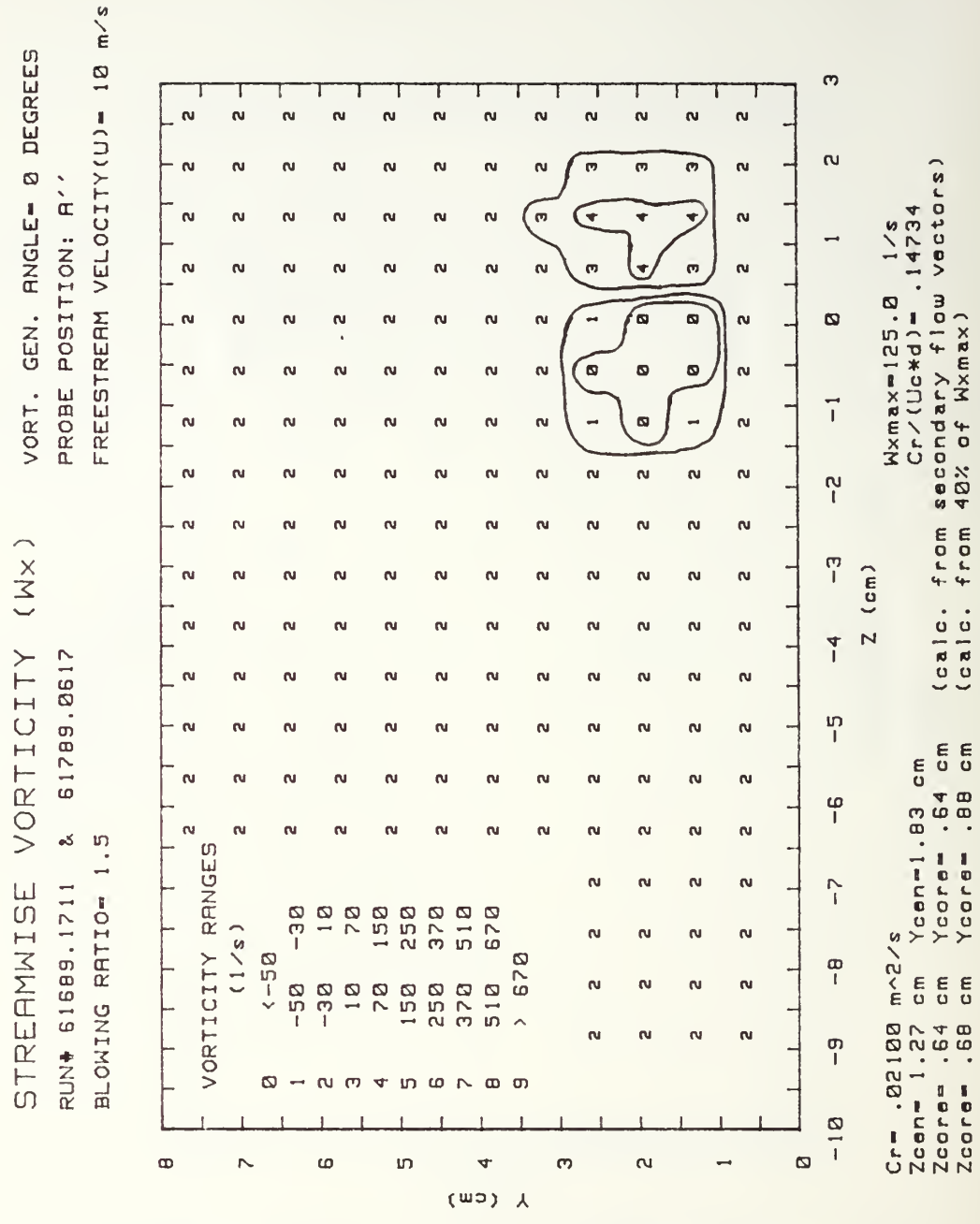

Figure 37. Streamwise Vorticity (Boundary Layer, Station A'', m = 1.5, Δ = 0.25)

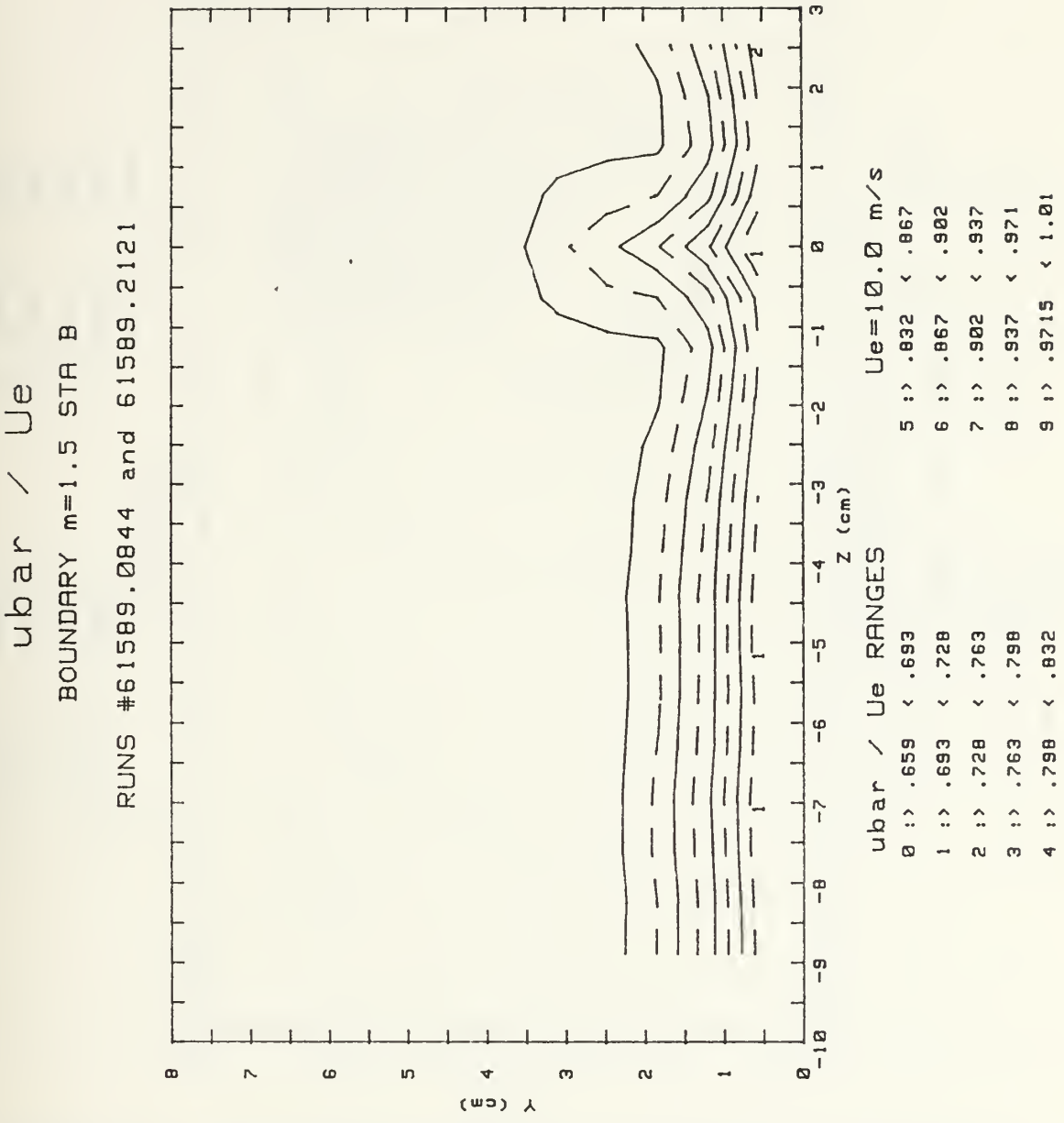

Figure 38. $\bar{u}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

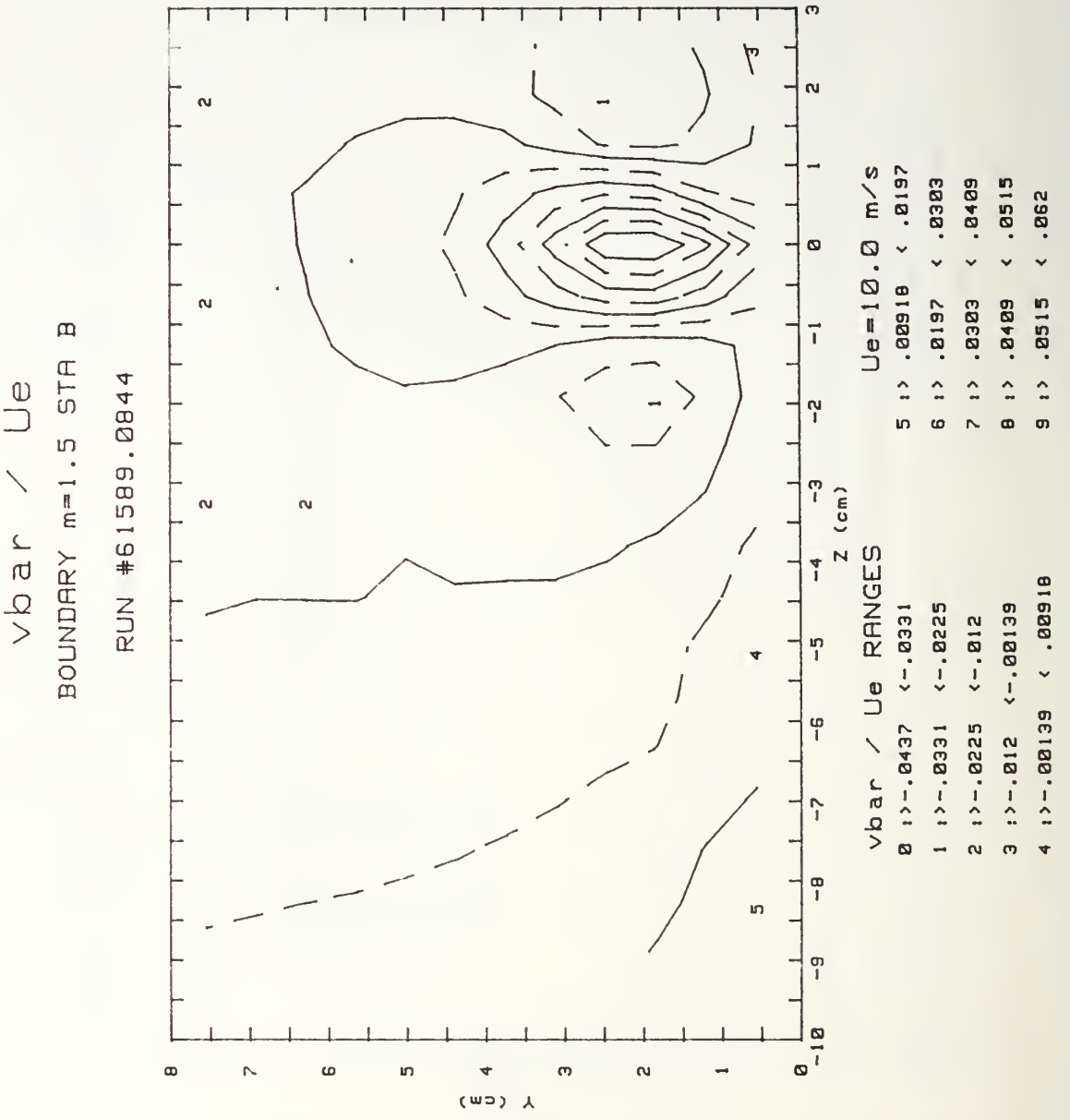

Figure 39. $\overline{v}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

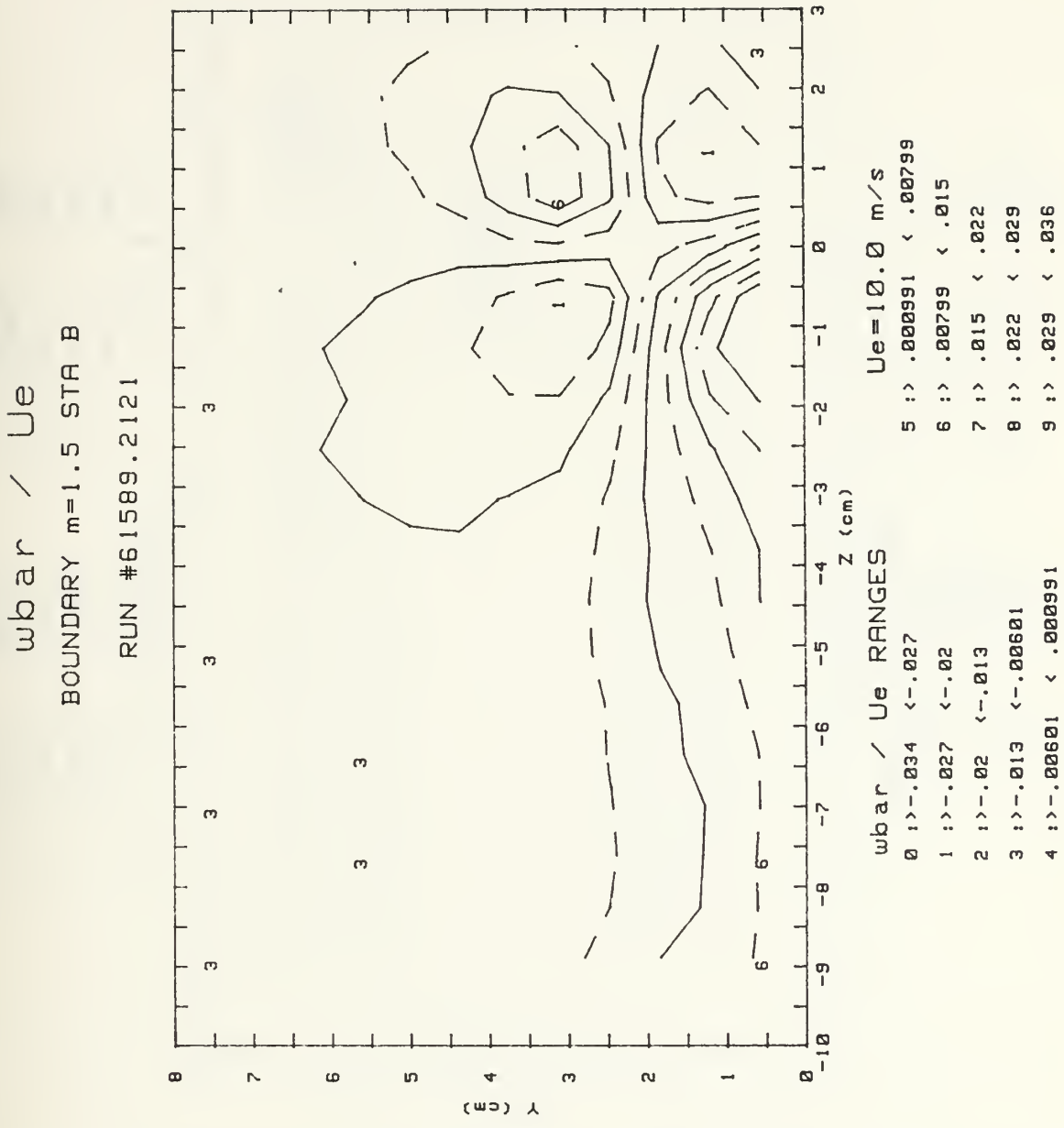

Figure 40. $\overline{w}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

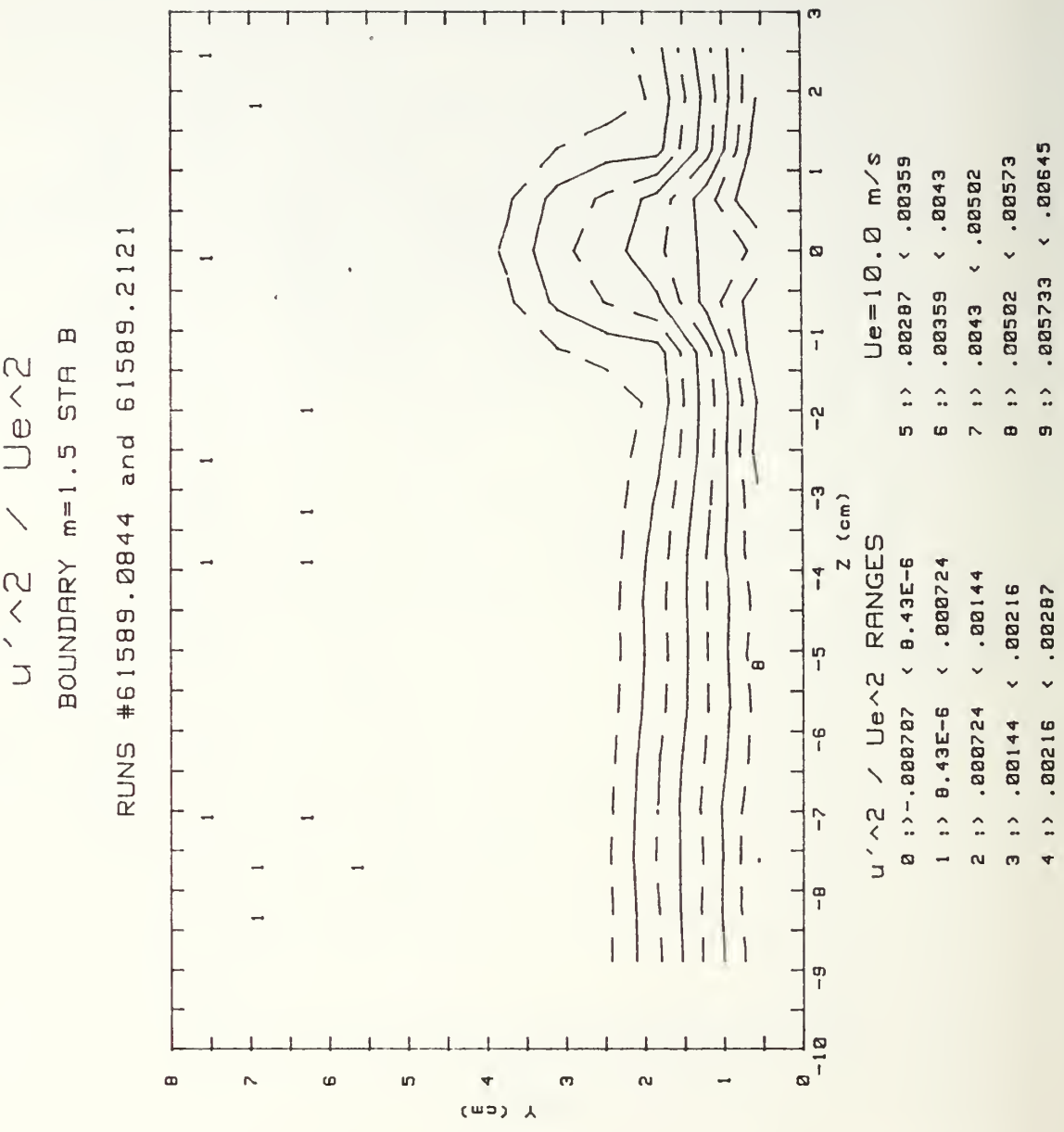

Figure 41. $\overline{u'^2}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

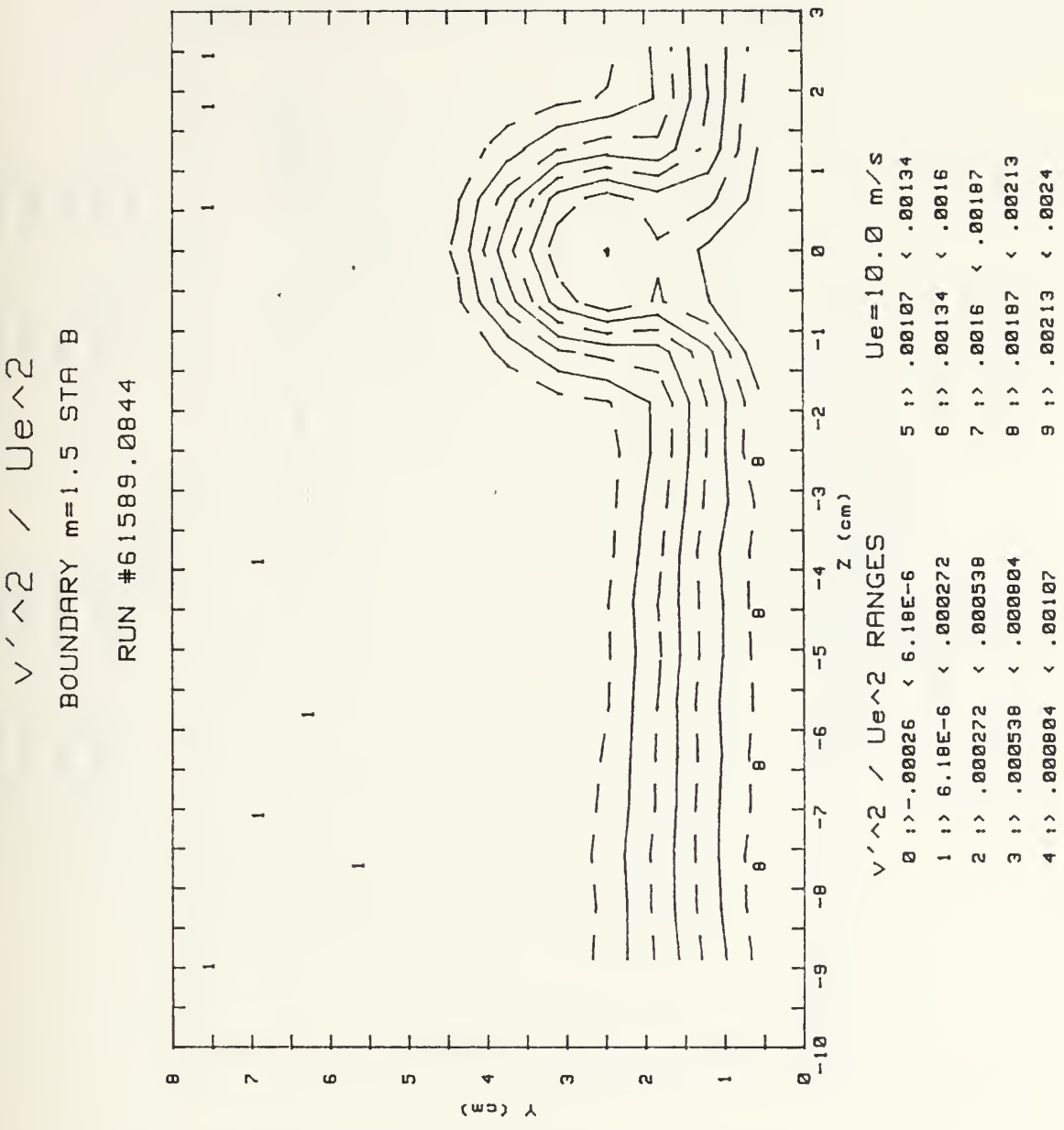

Figure 42. $\overline{v'^2}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

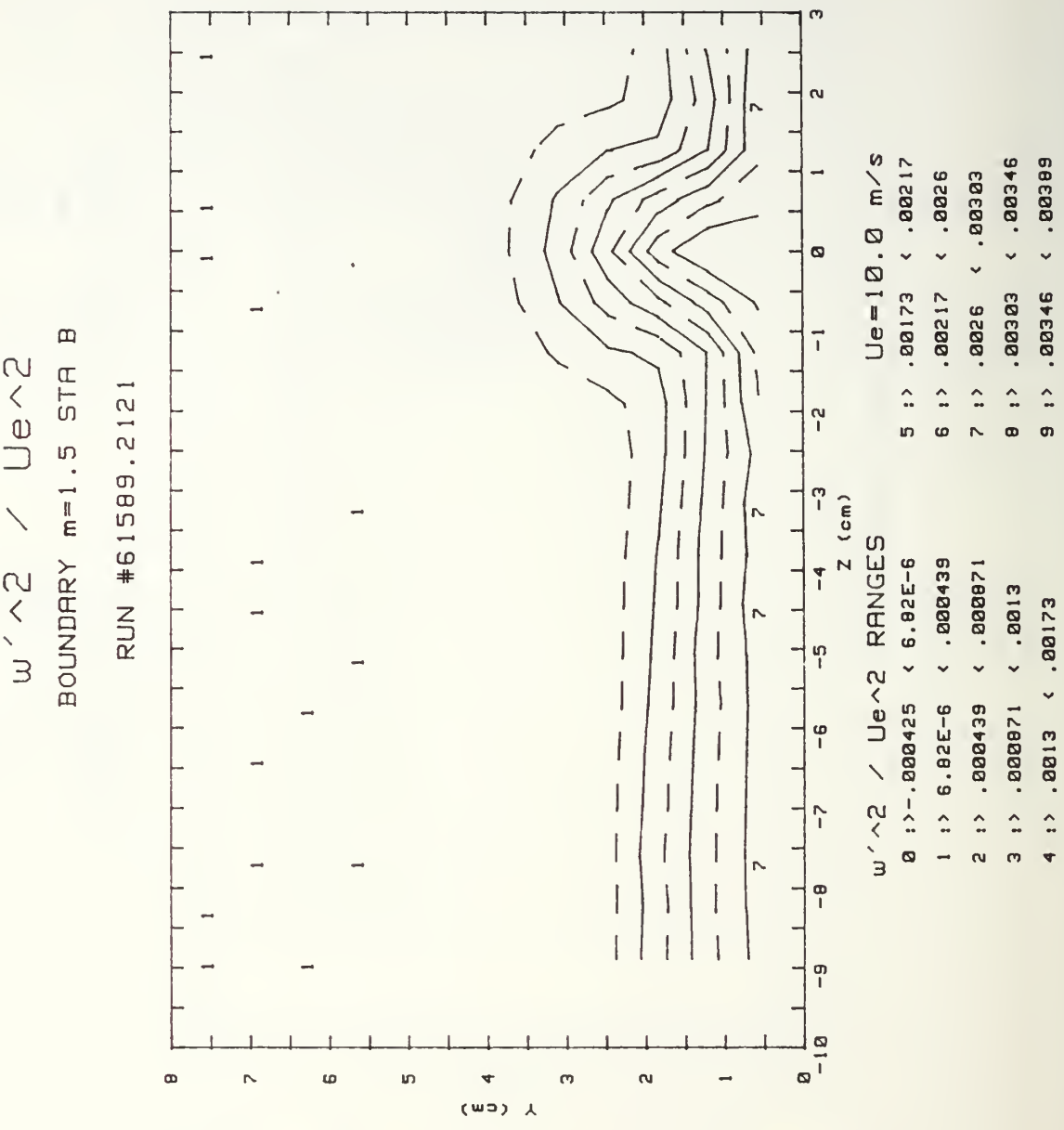

Figure 43. $\overline{w'^2}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

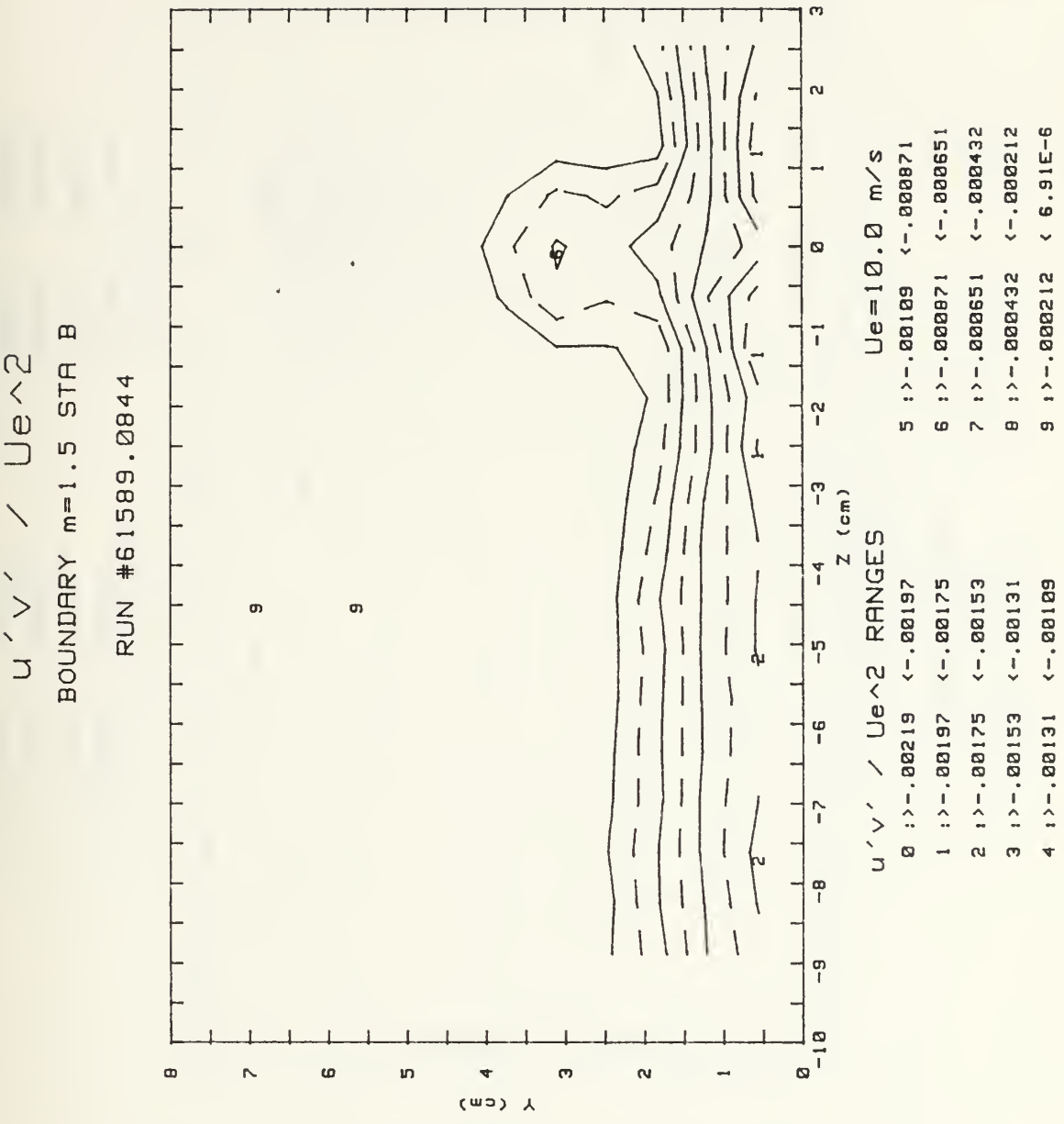

Figure 44. $\overline{u'v'}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

Figure 45. $\overline{u'w'}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

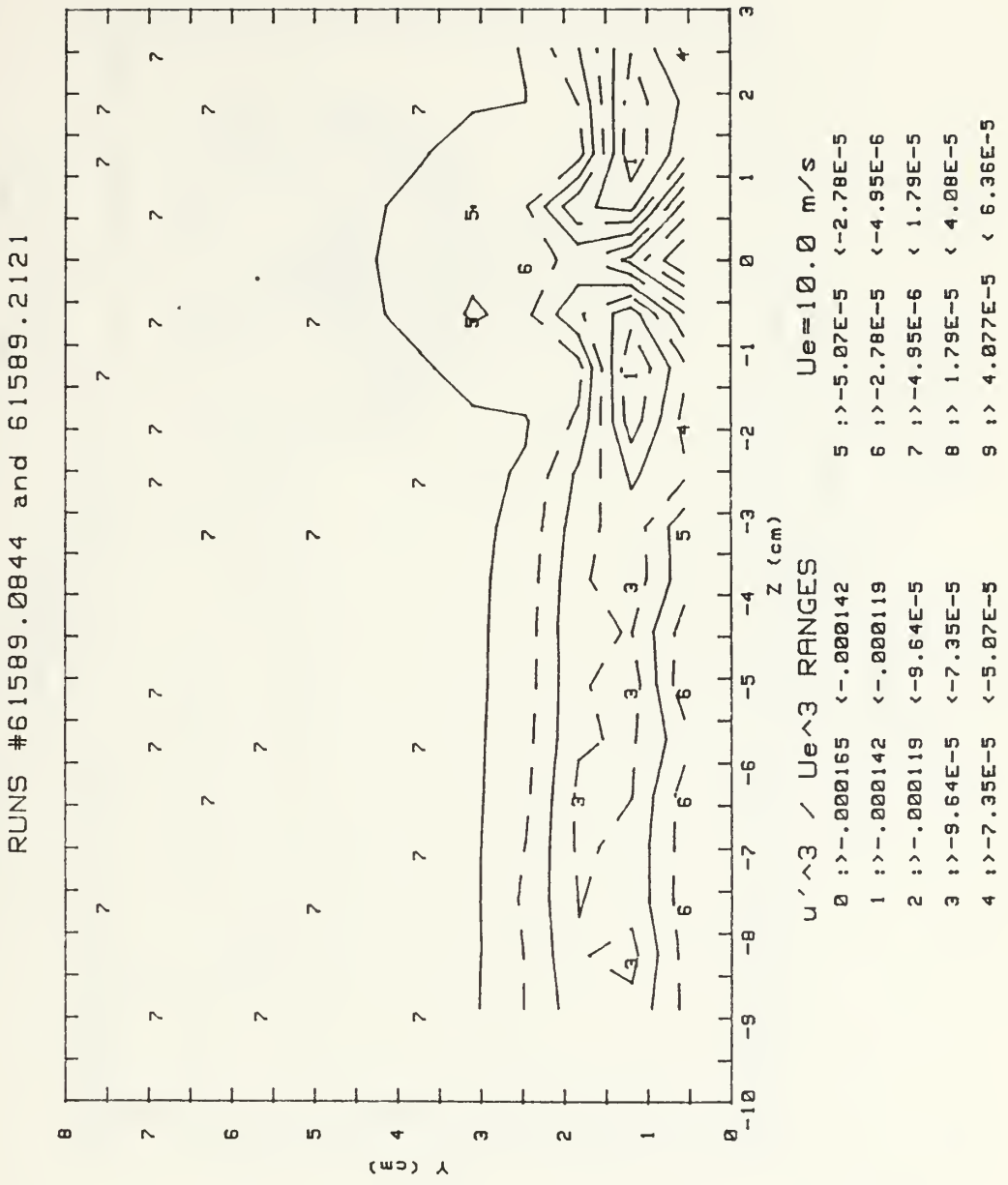

Figure 46. $\overline{u'^3}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

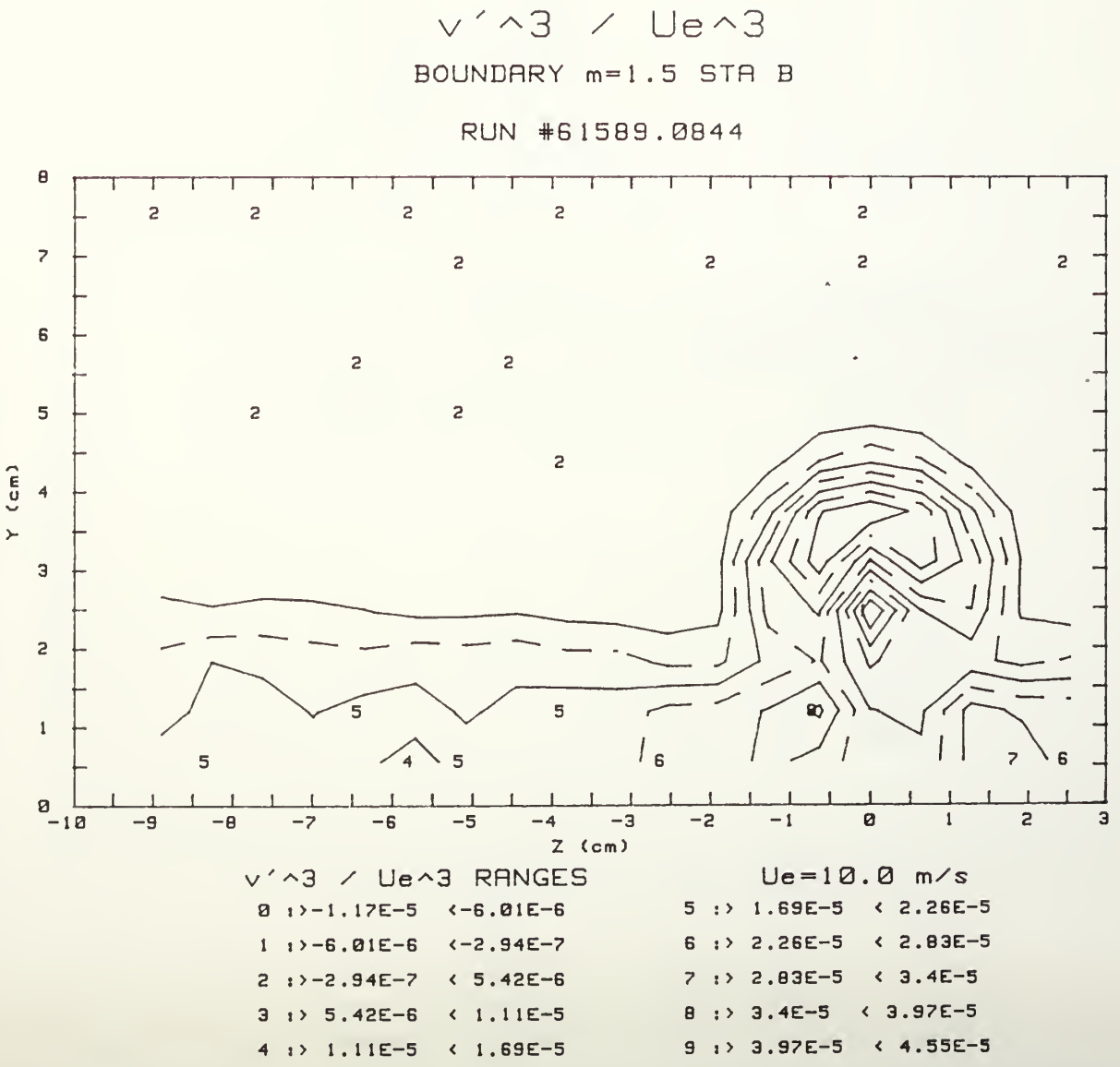

Figure 47. $\overline{v'^3}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

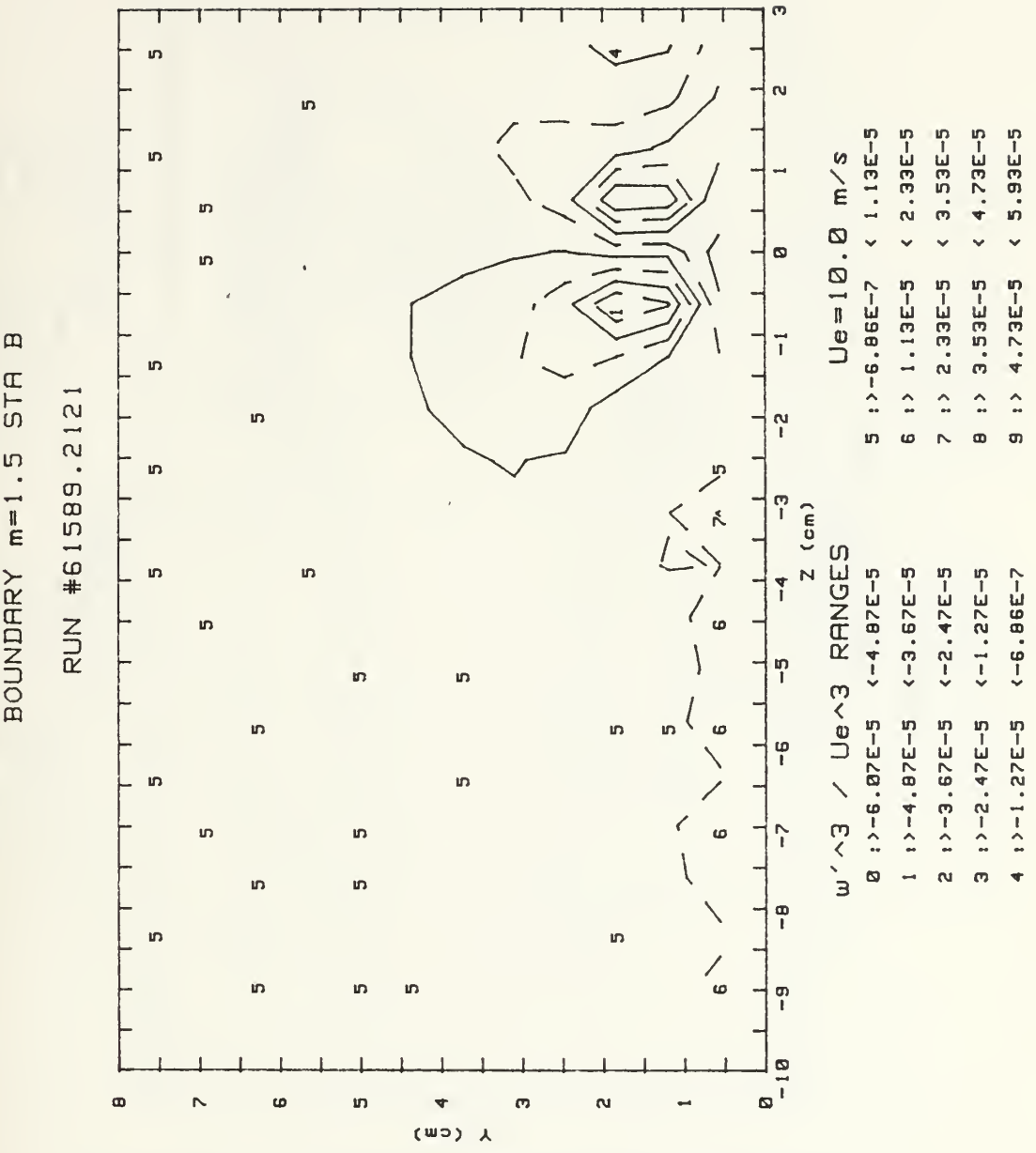

Figure 48. $\overline{w'^3}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

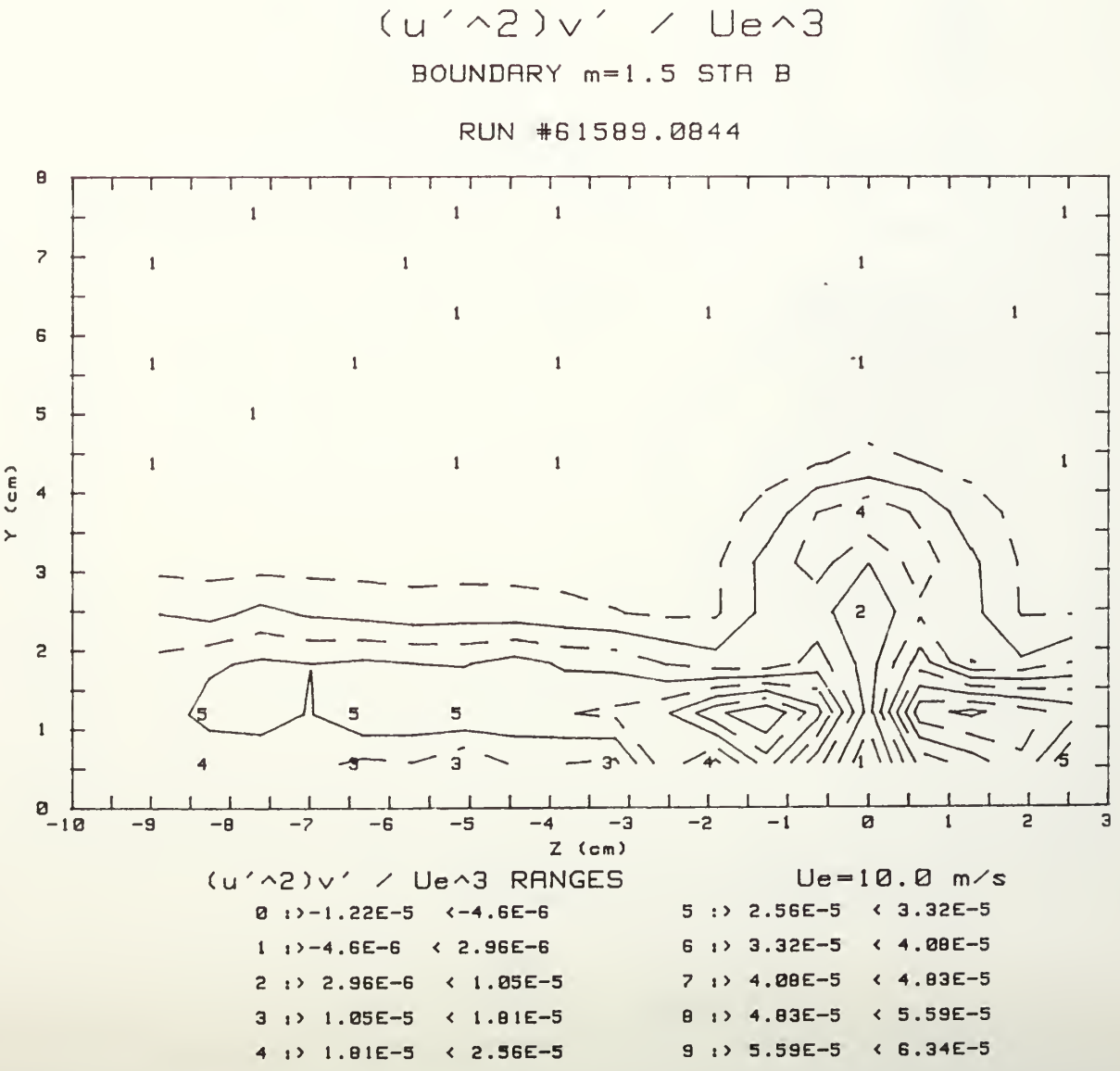

Figure 49. $\overline{u'^2v'}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

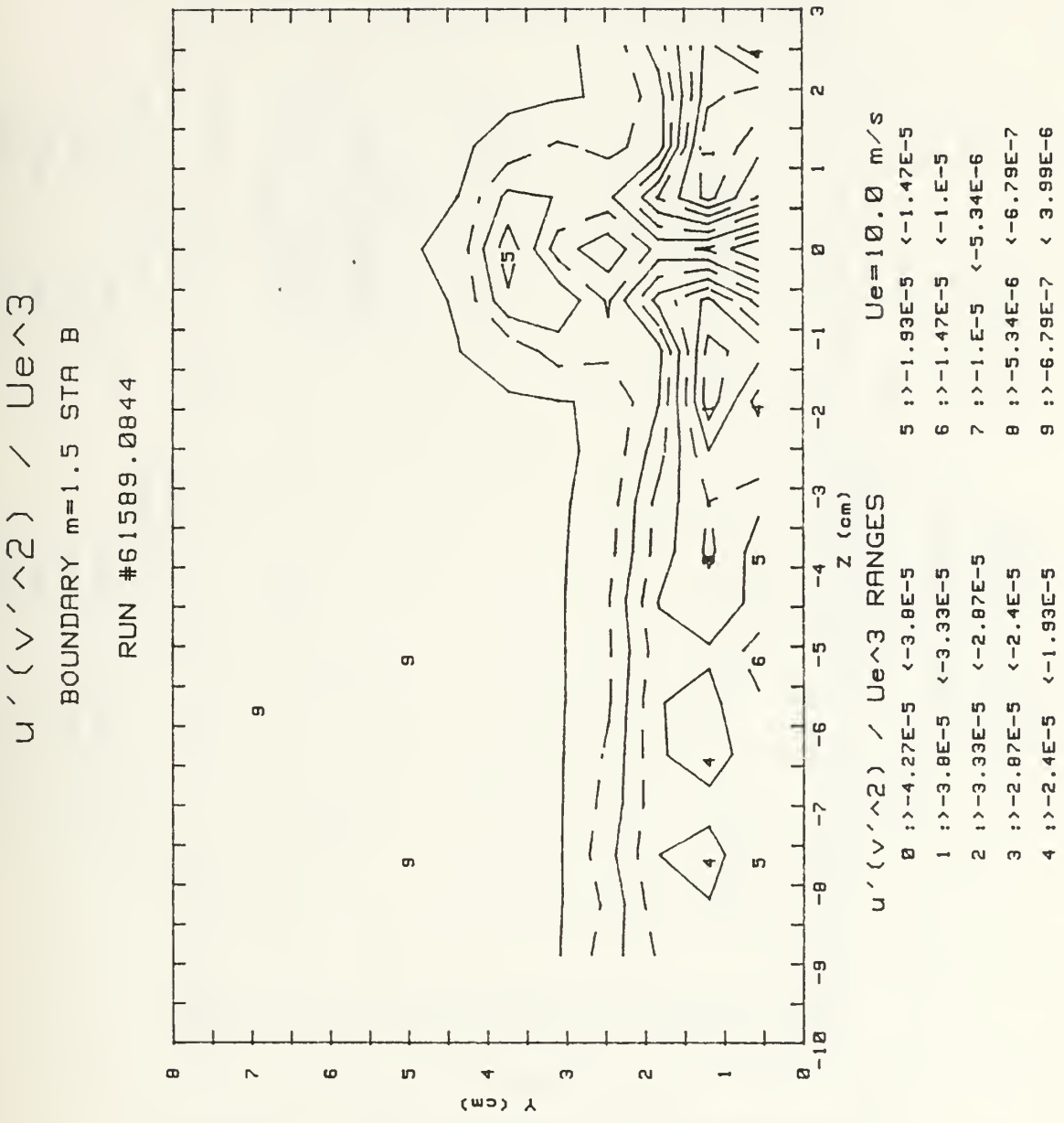

Figure 50. $\overline{u'v'^2}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

Figure 51. $\overline{u'^2w'}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

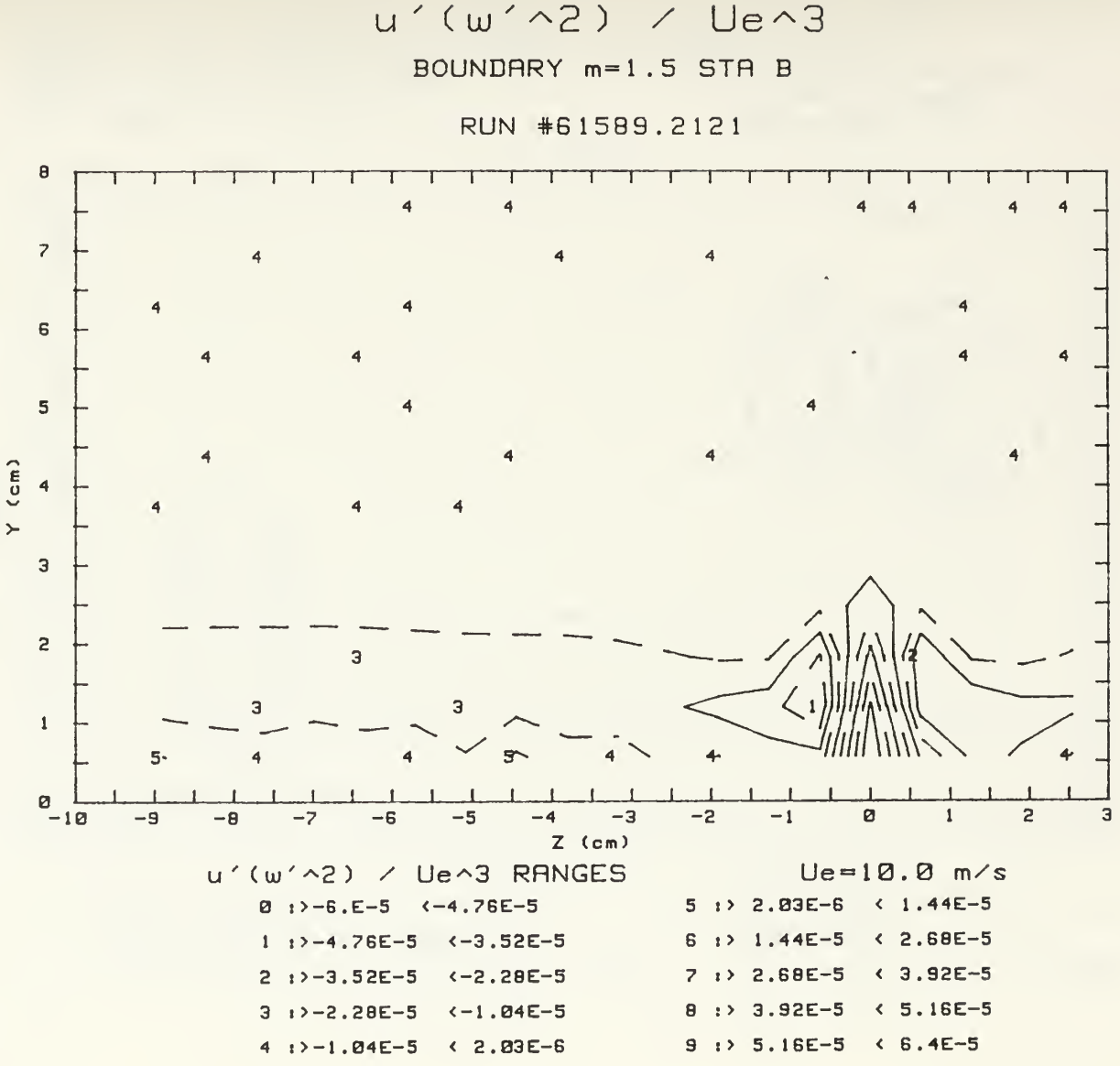

Figure 52. $\overline{u'w'^2}$ (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

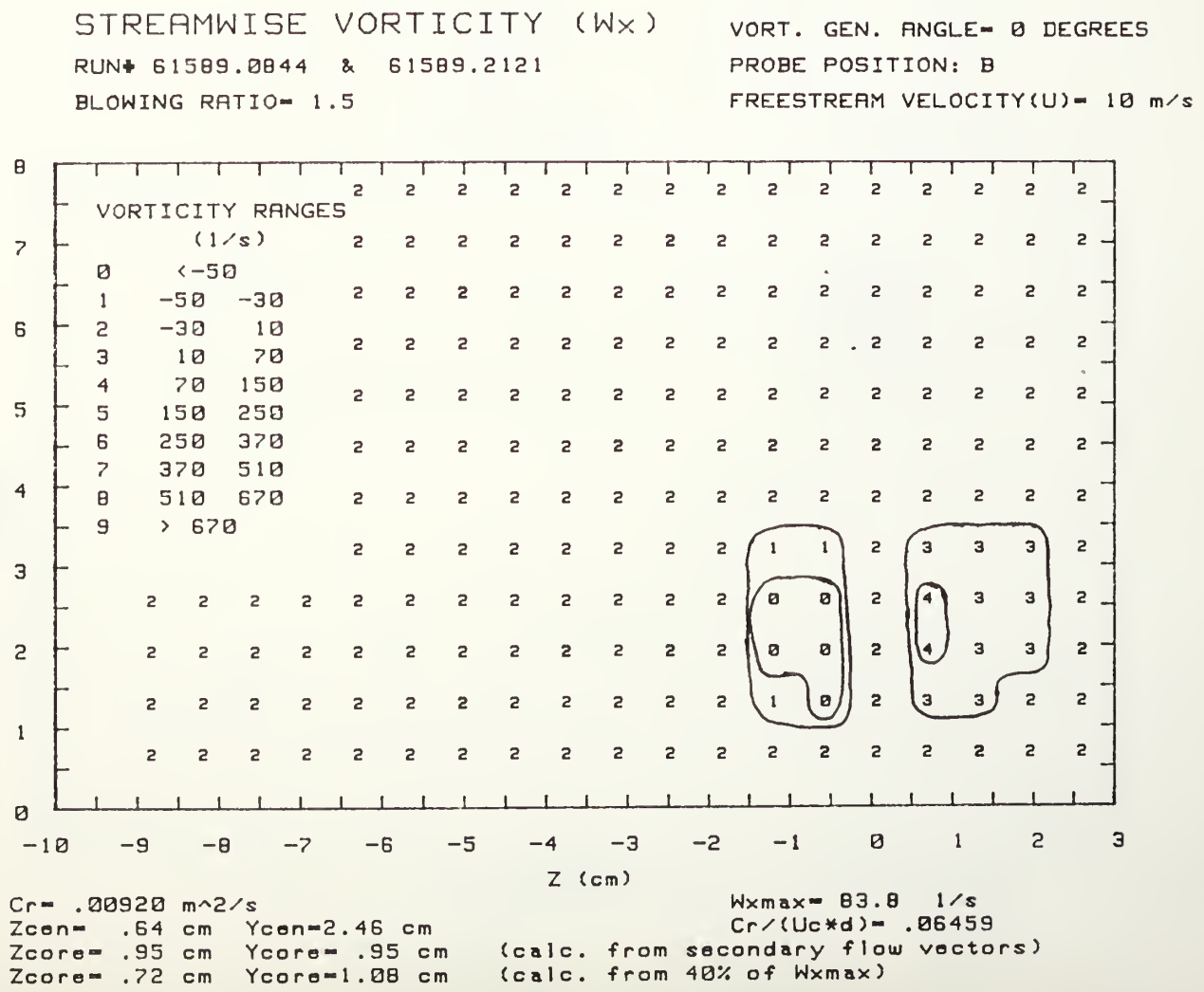

Figure 53. Streamwise Vorticity (Boundary Layer, Station B, m = 1.5, Δ = 0.25)

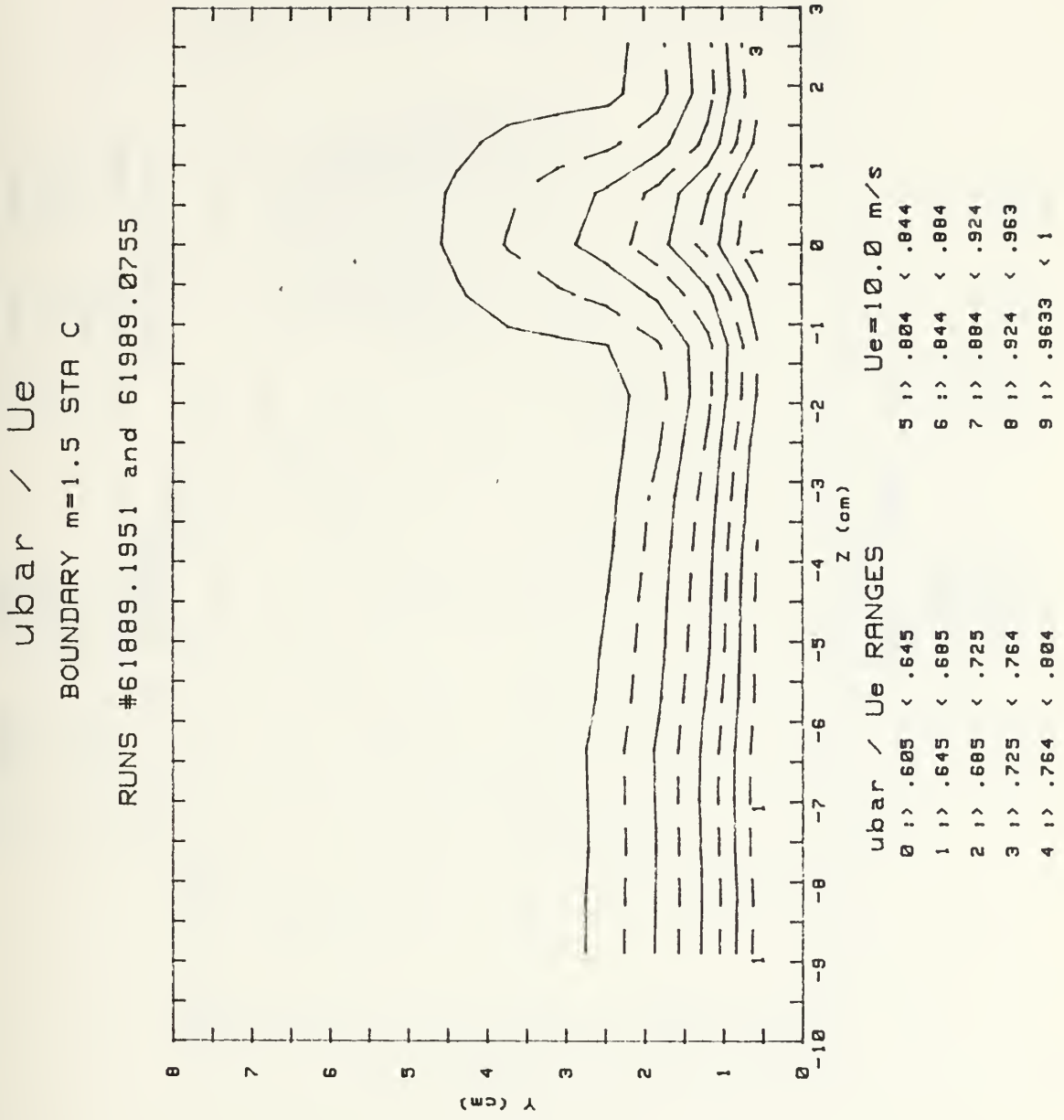

Figure 54. $\bar{u}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

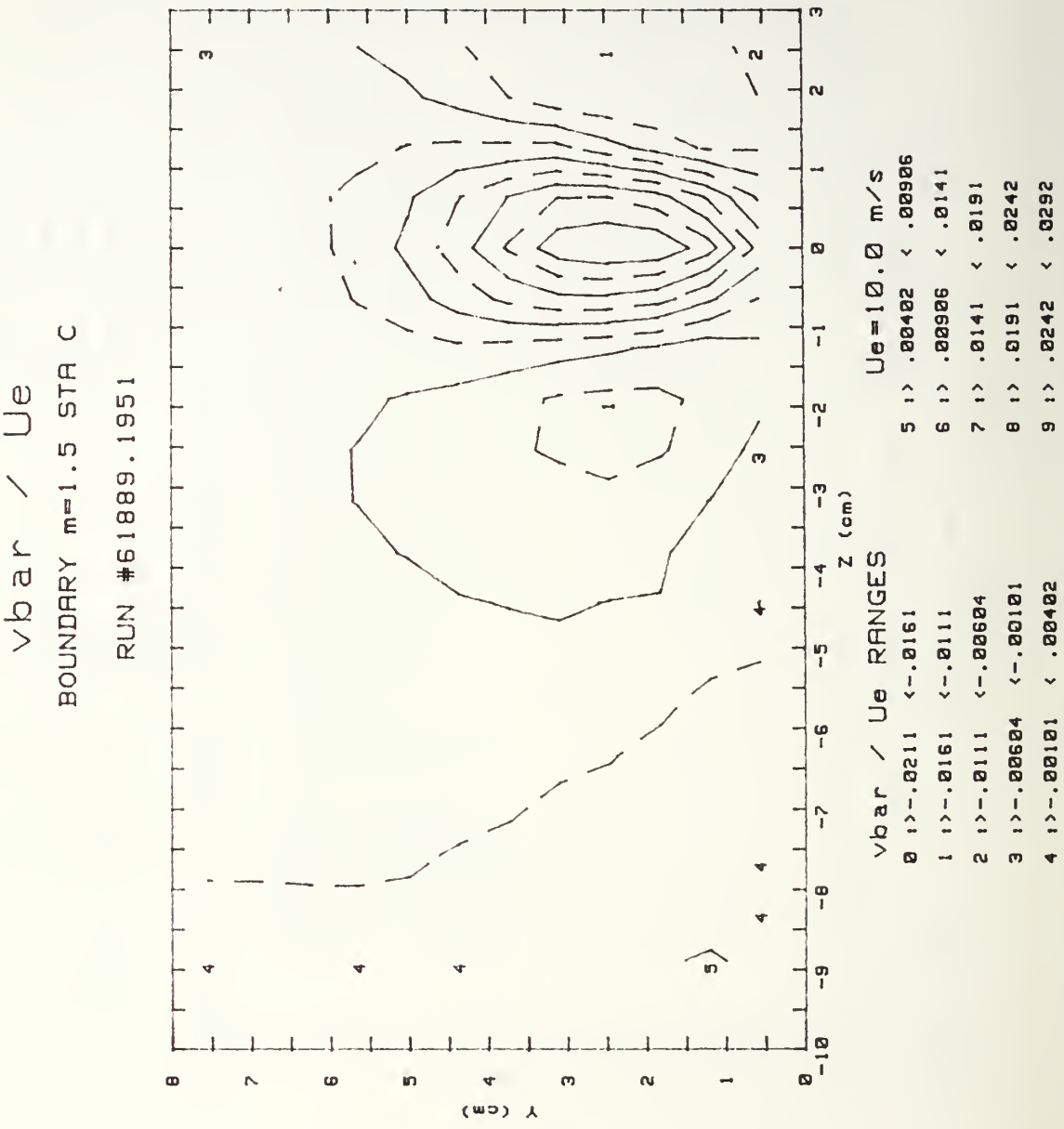

Figure 55. $\bar{v}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

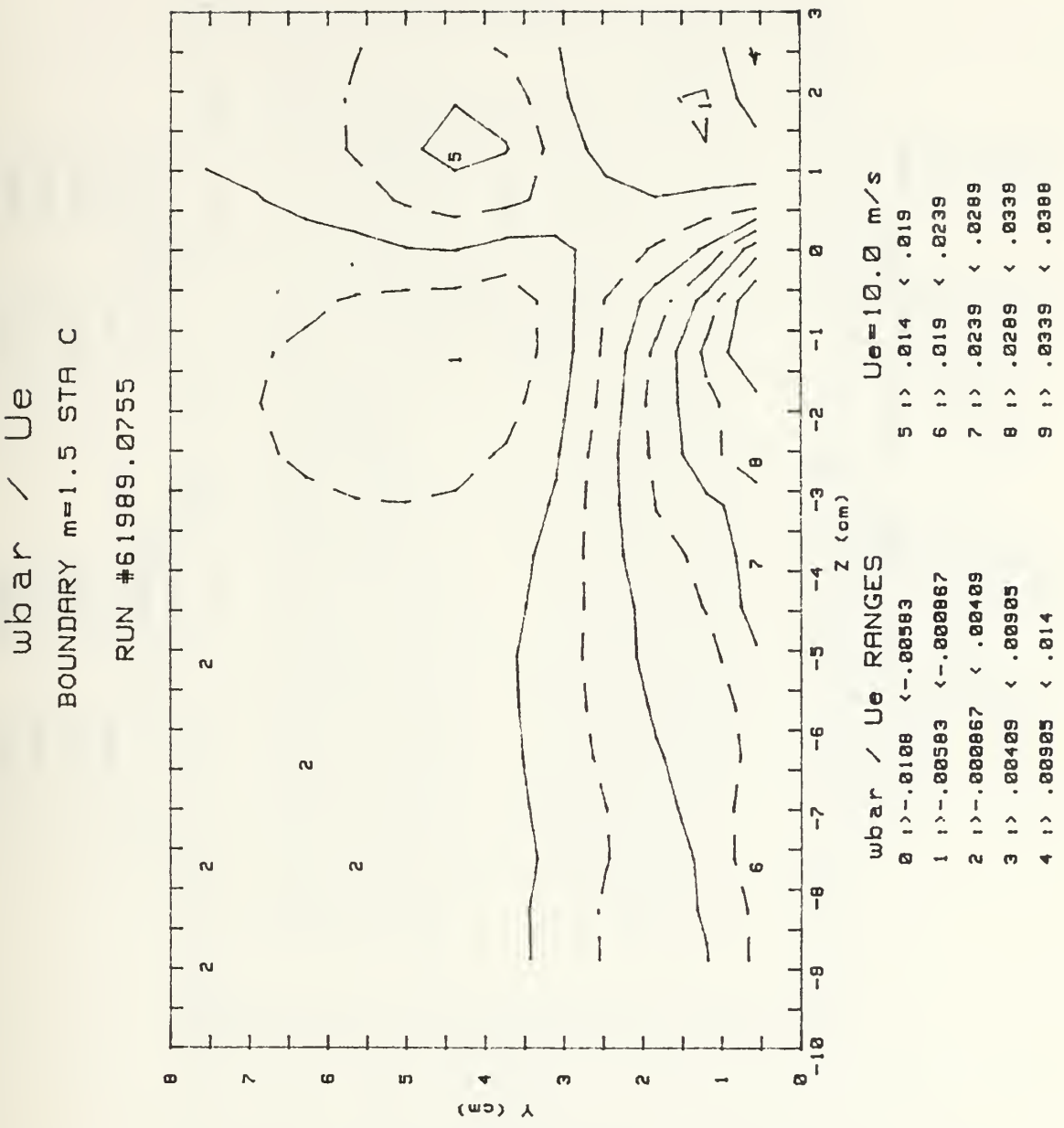

Figure 56. $\overline{w}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

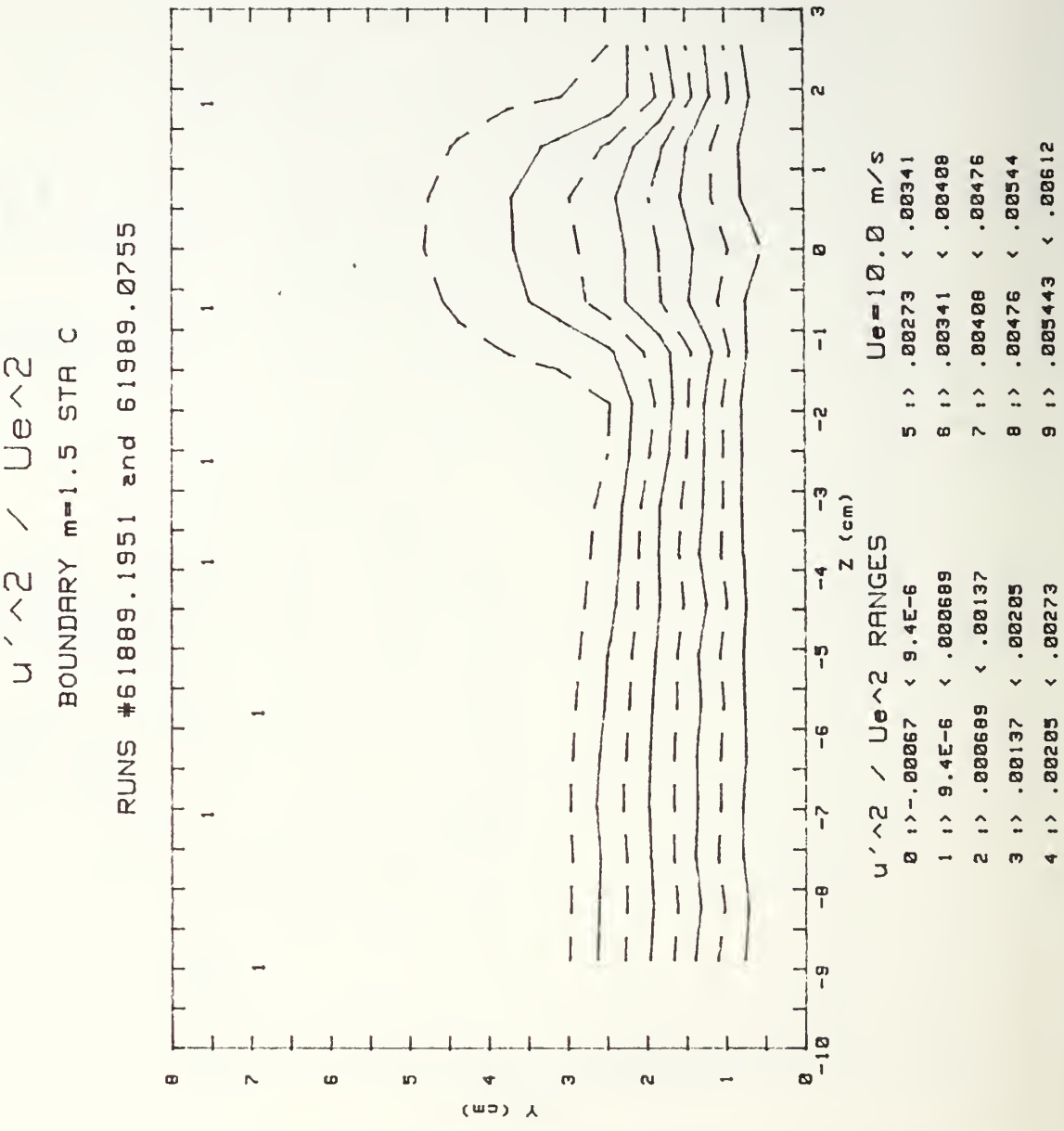

Figure 57. $\overline{u'^2}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

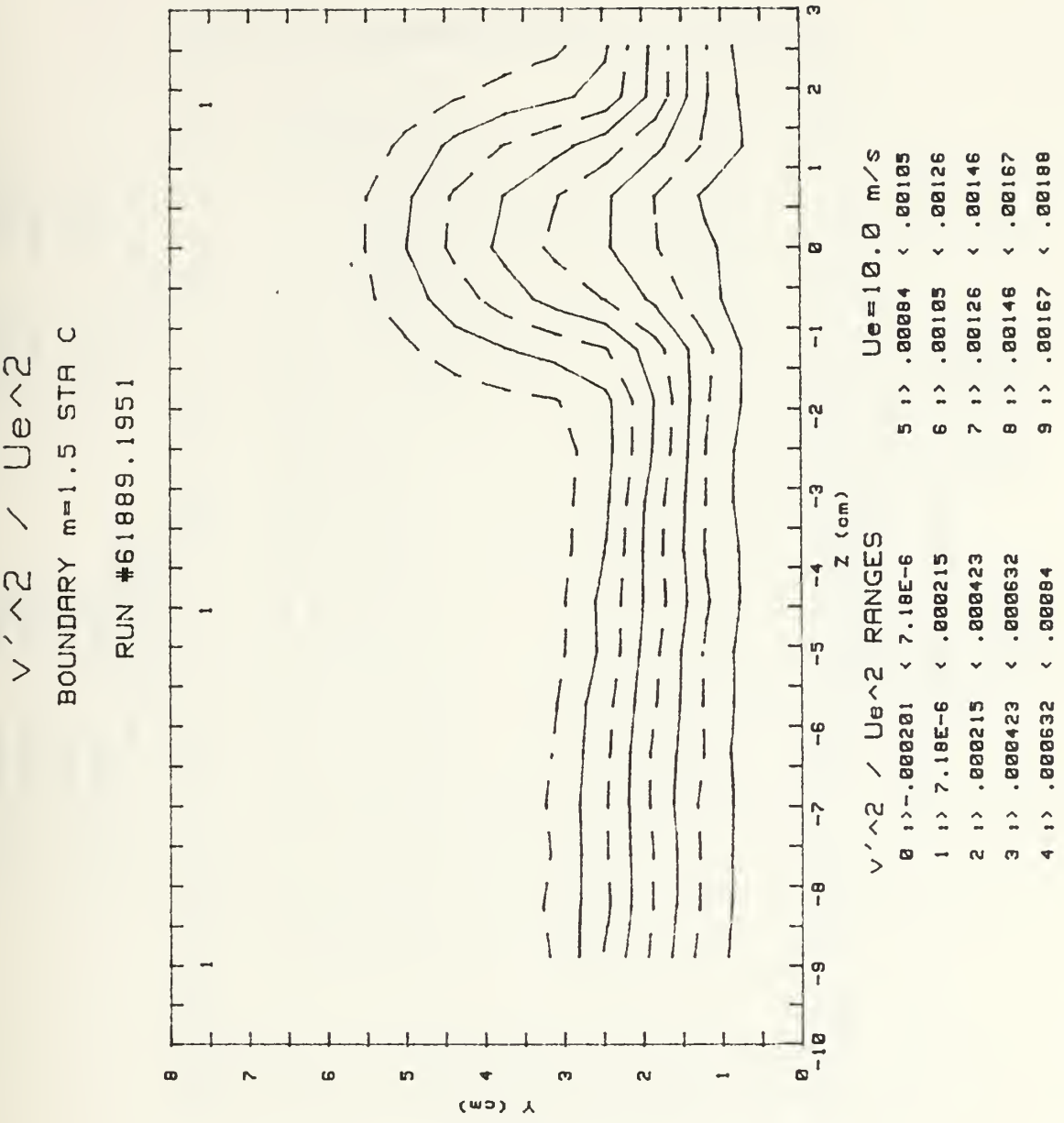

Figure 58. $\overline{v'^2}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

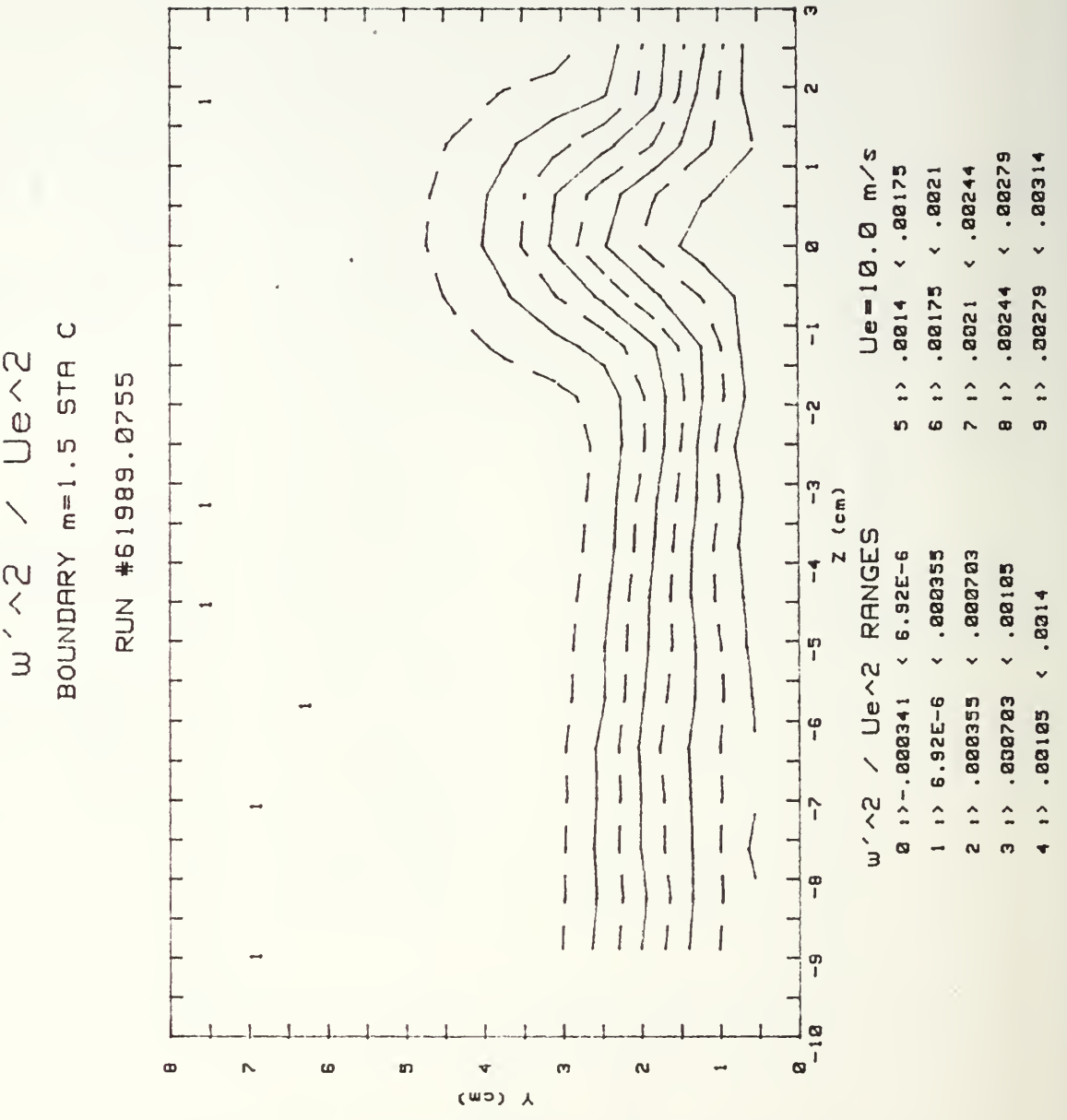

Figure 59. $\overline{w'^2}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

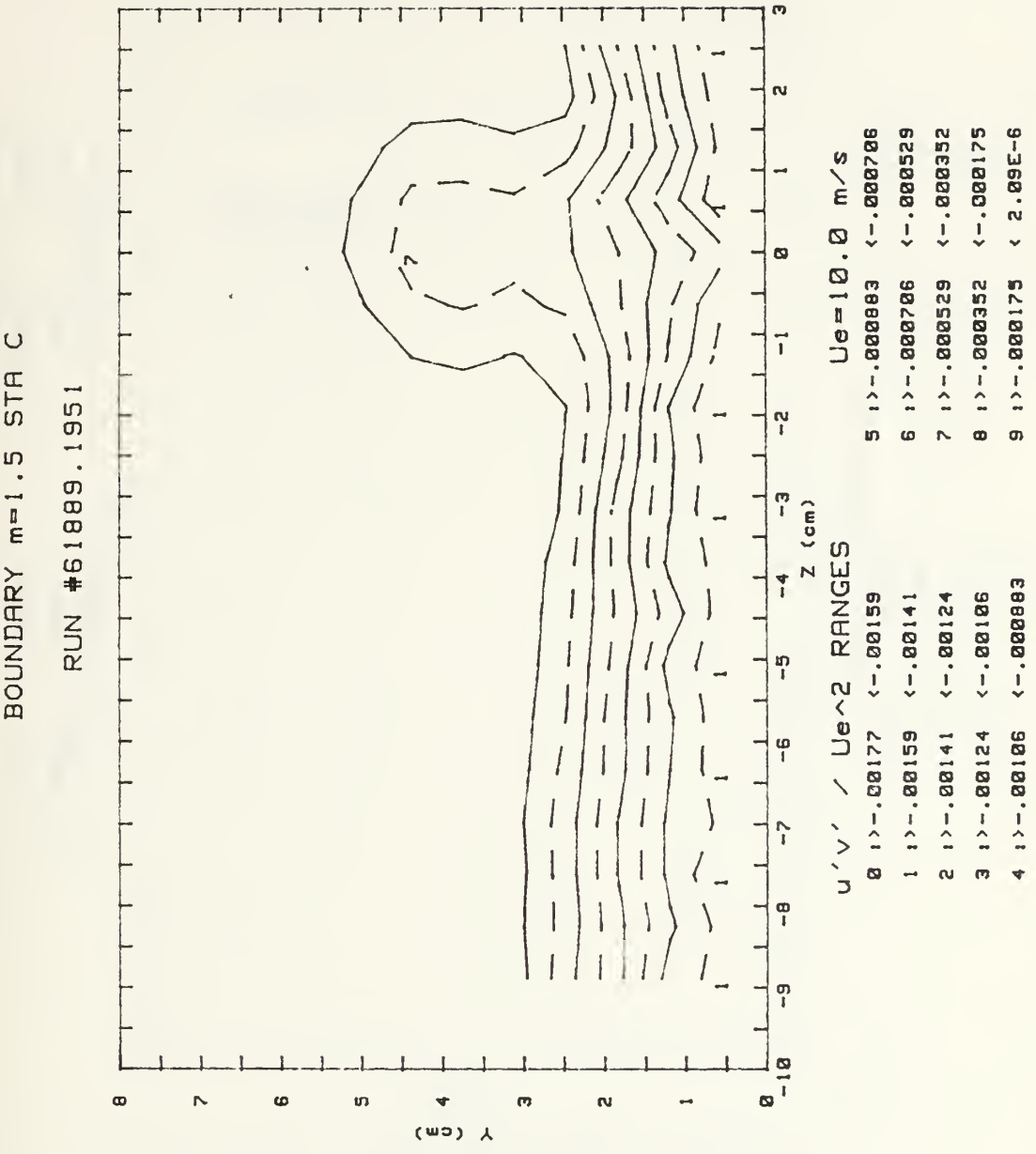

Figure 60. $\overline{u'v'}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

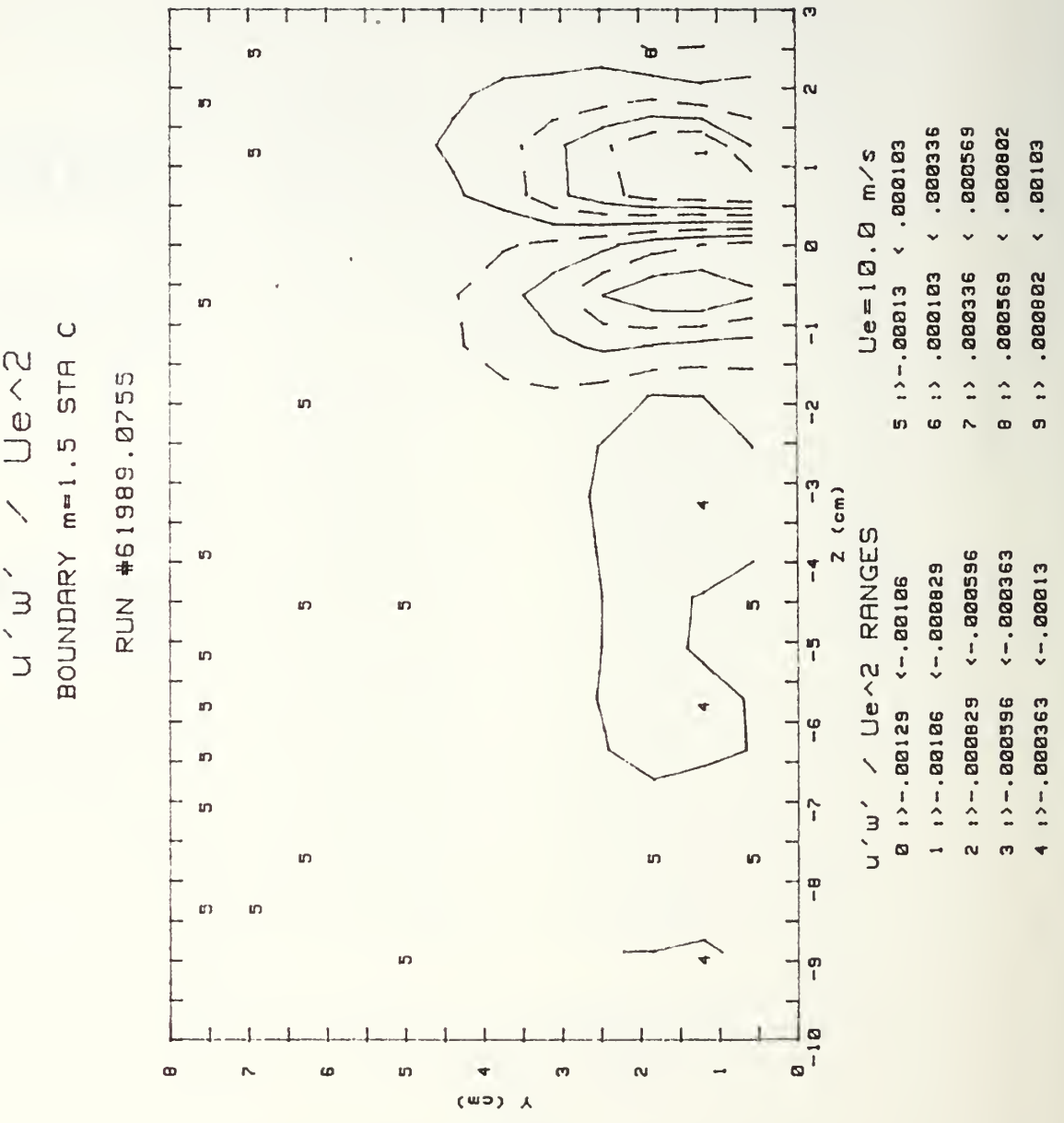

Figure 61. $\overline{u'w'}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

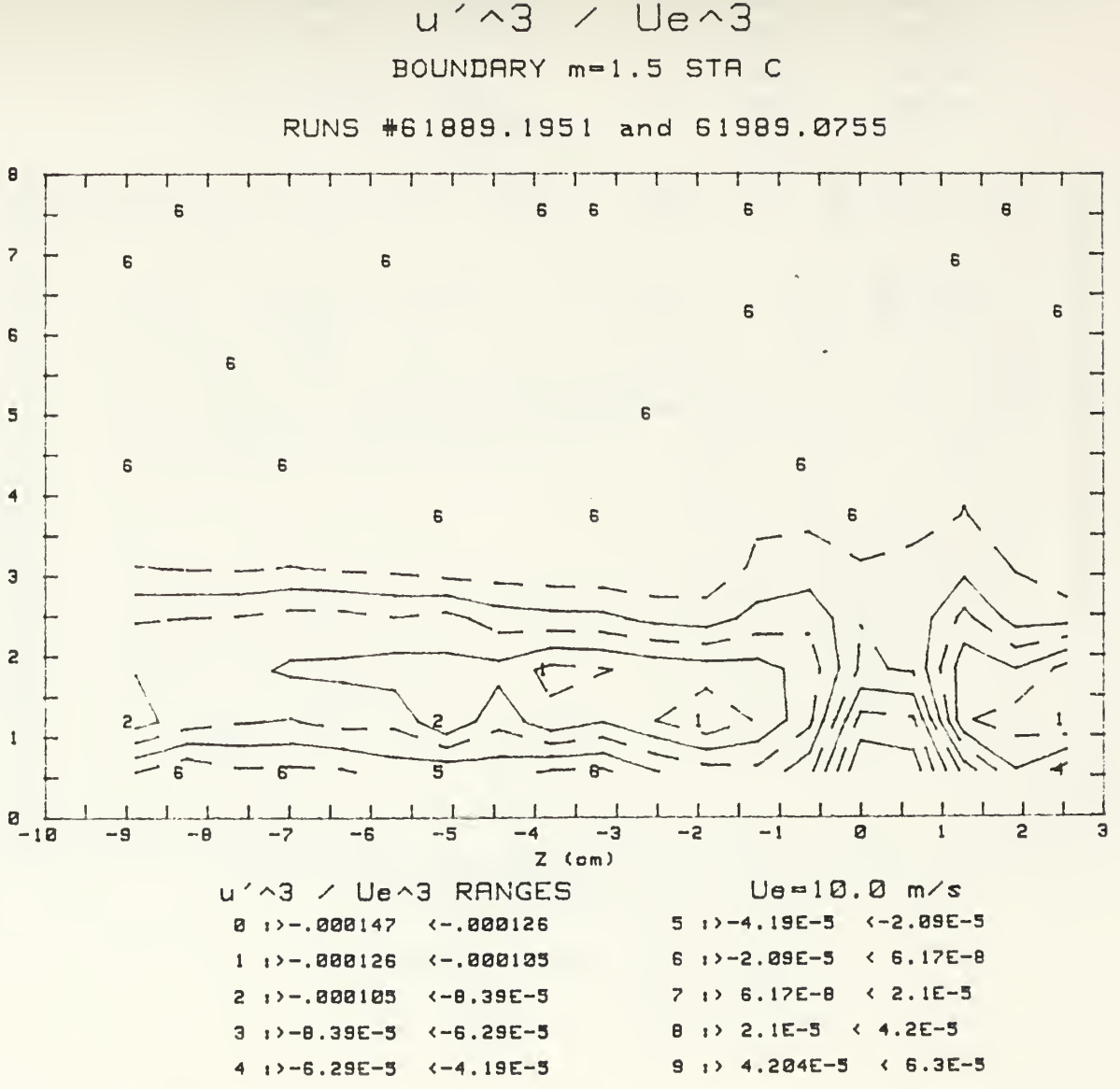

Figure 62. $\overline{u'^3}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

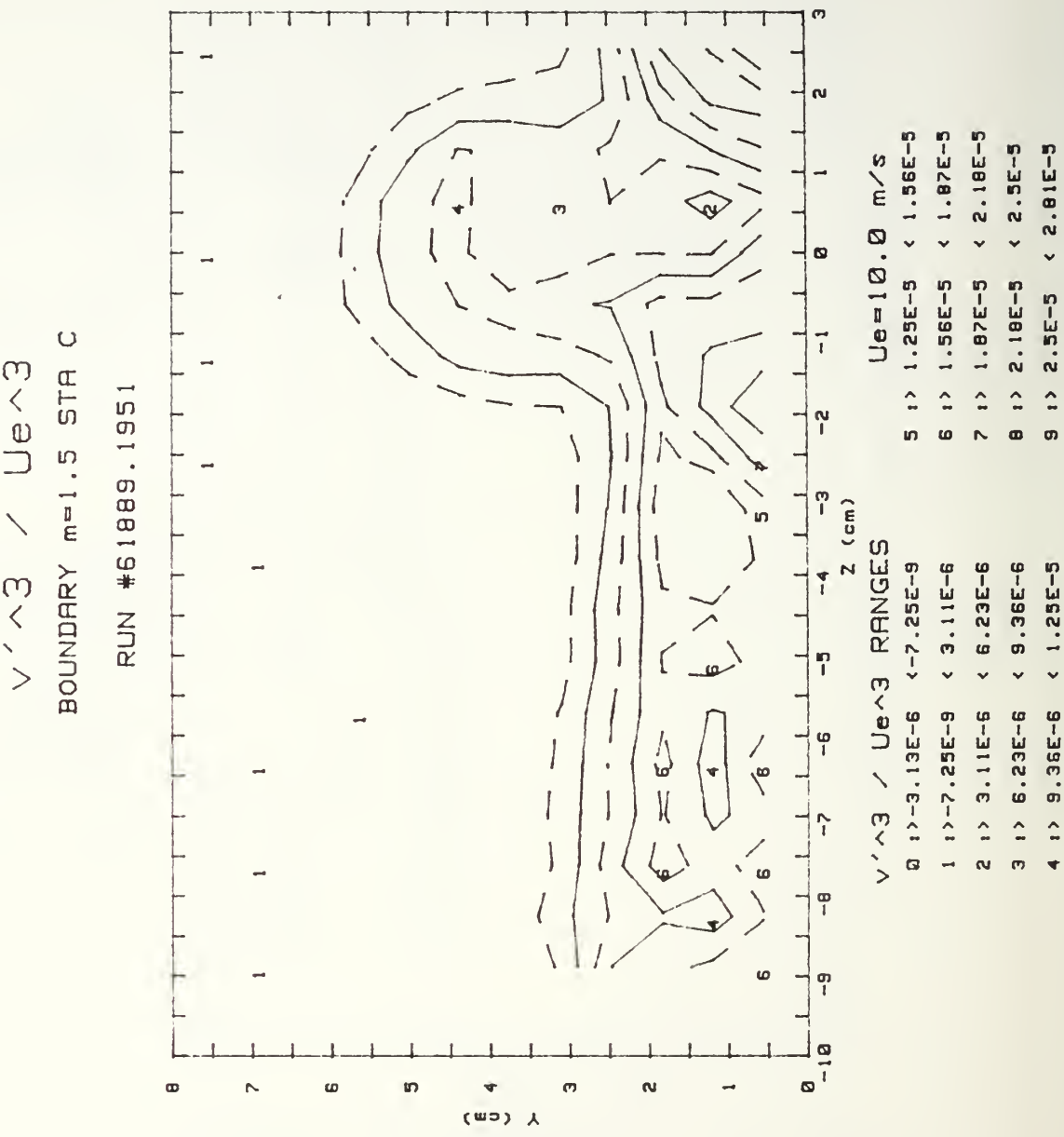

Figure 63. $\overline{v'^3}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

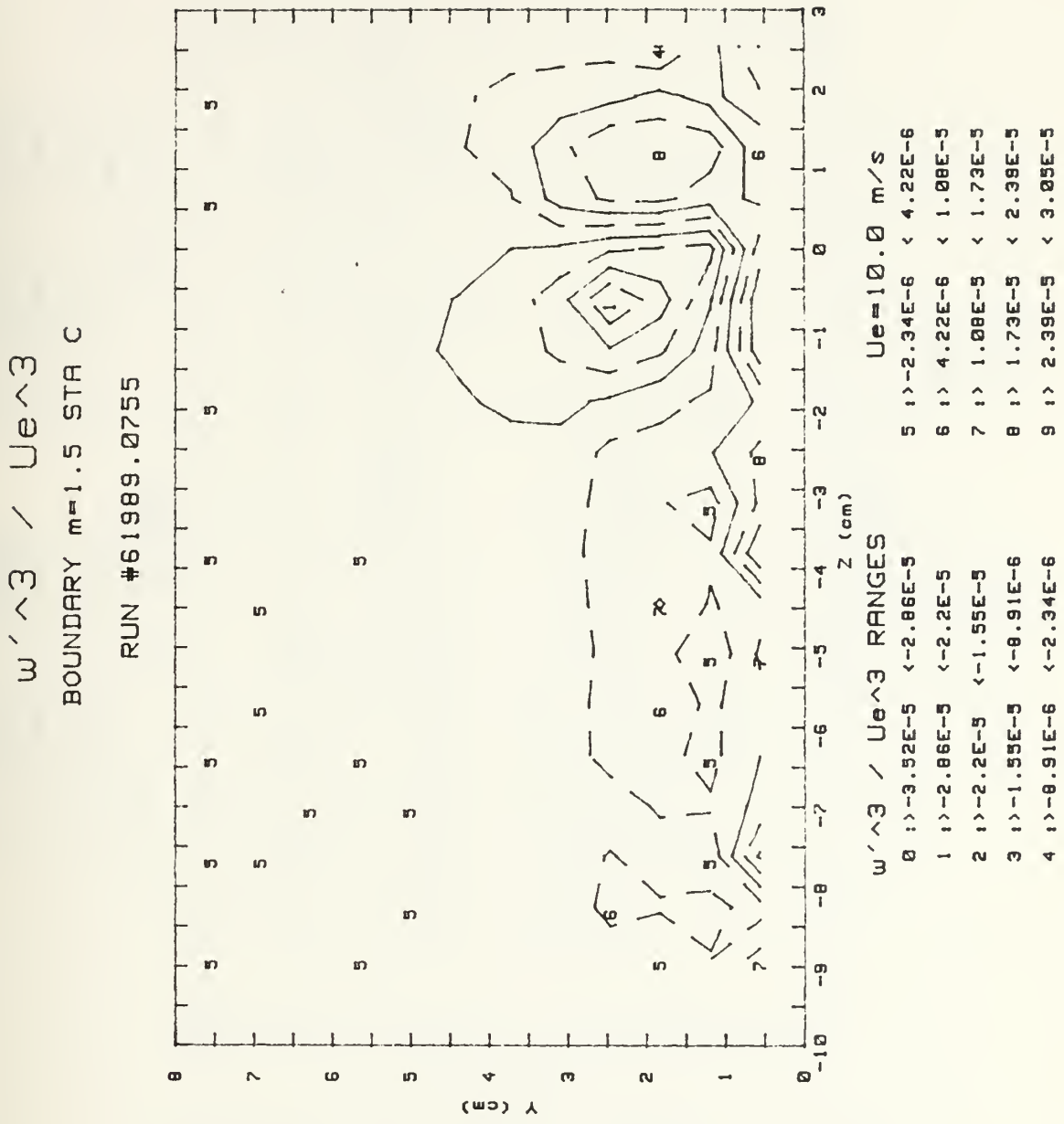

Figure 64. $\overline{w'^3}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

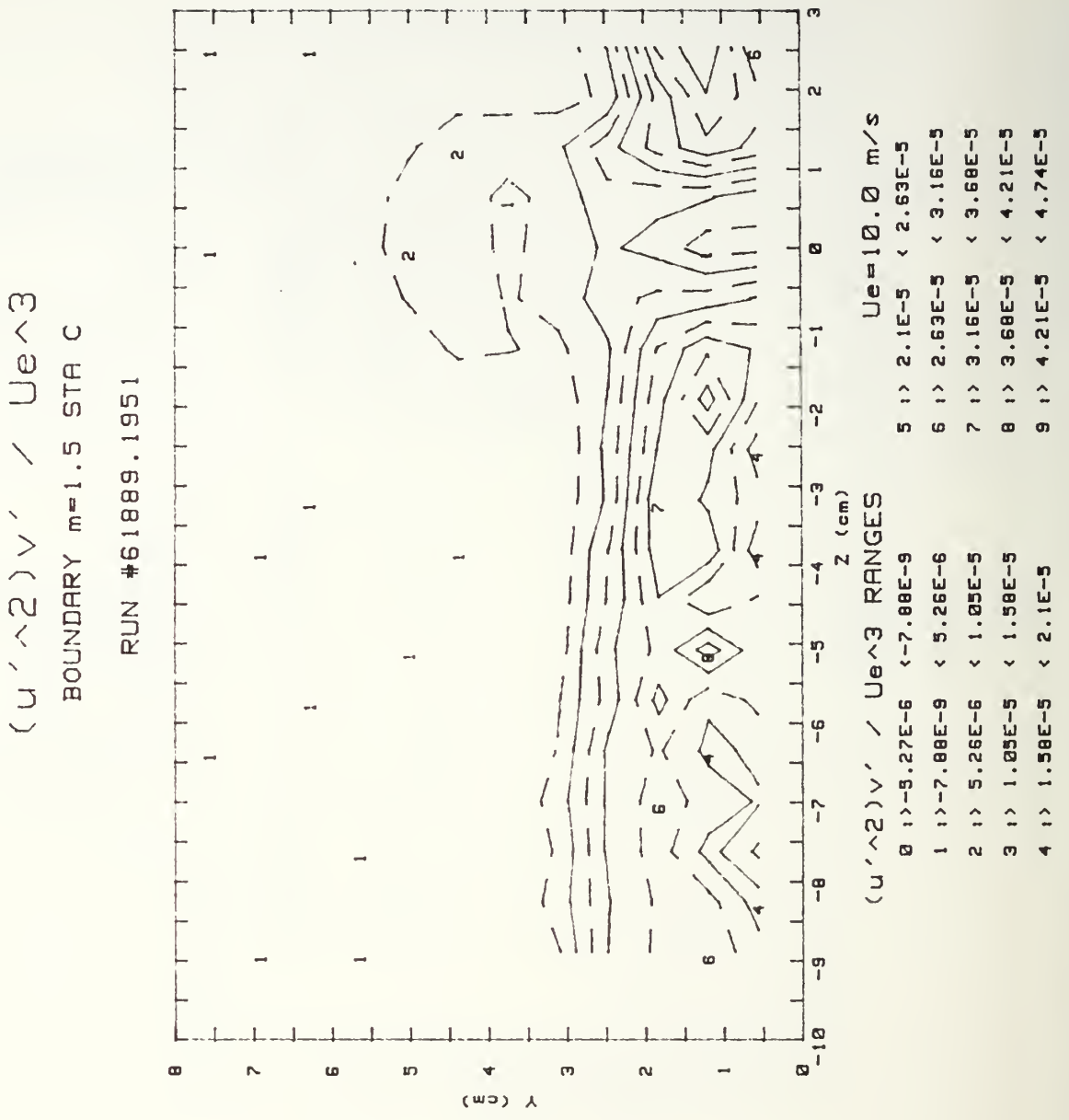

Figure 65. $\overline{u'^2v'}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

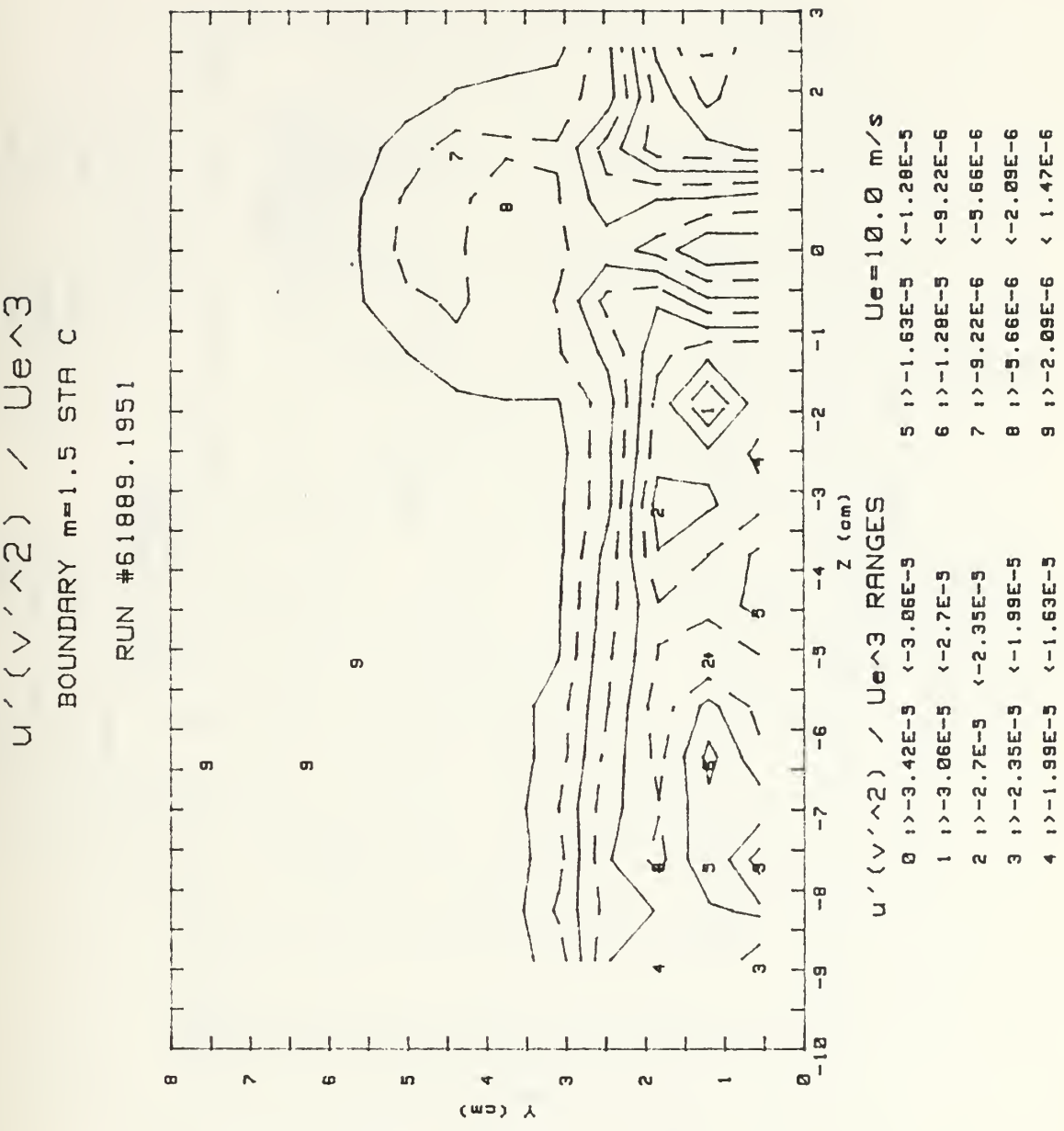

Figure 66. $\overline{u'v'^2}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

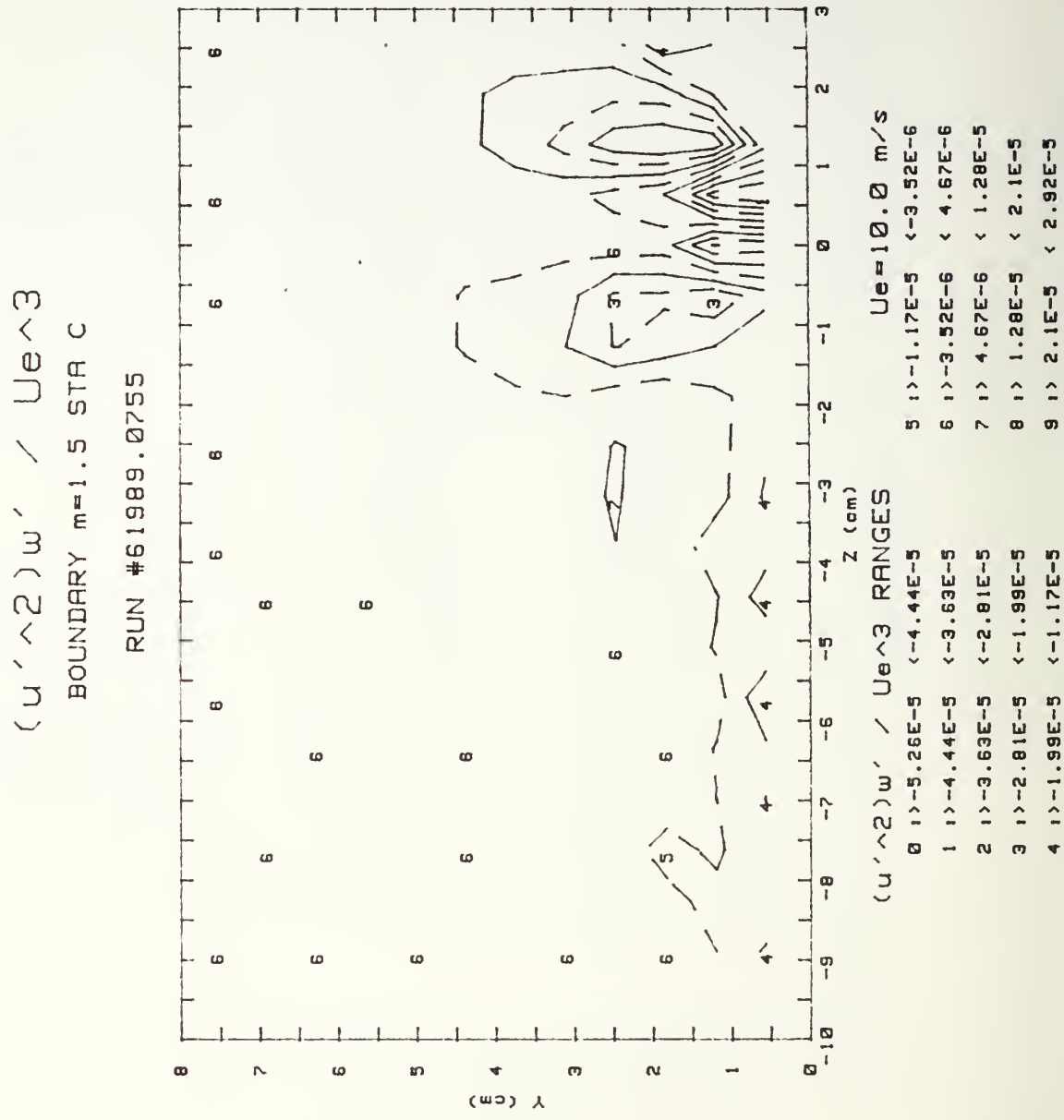

Figure 67. $\overline{u'^2w'}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

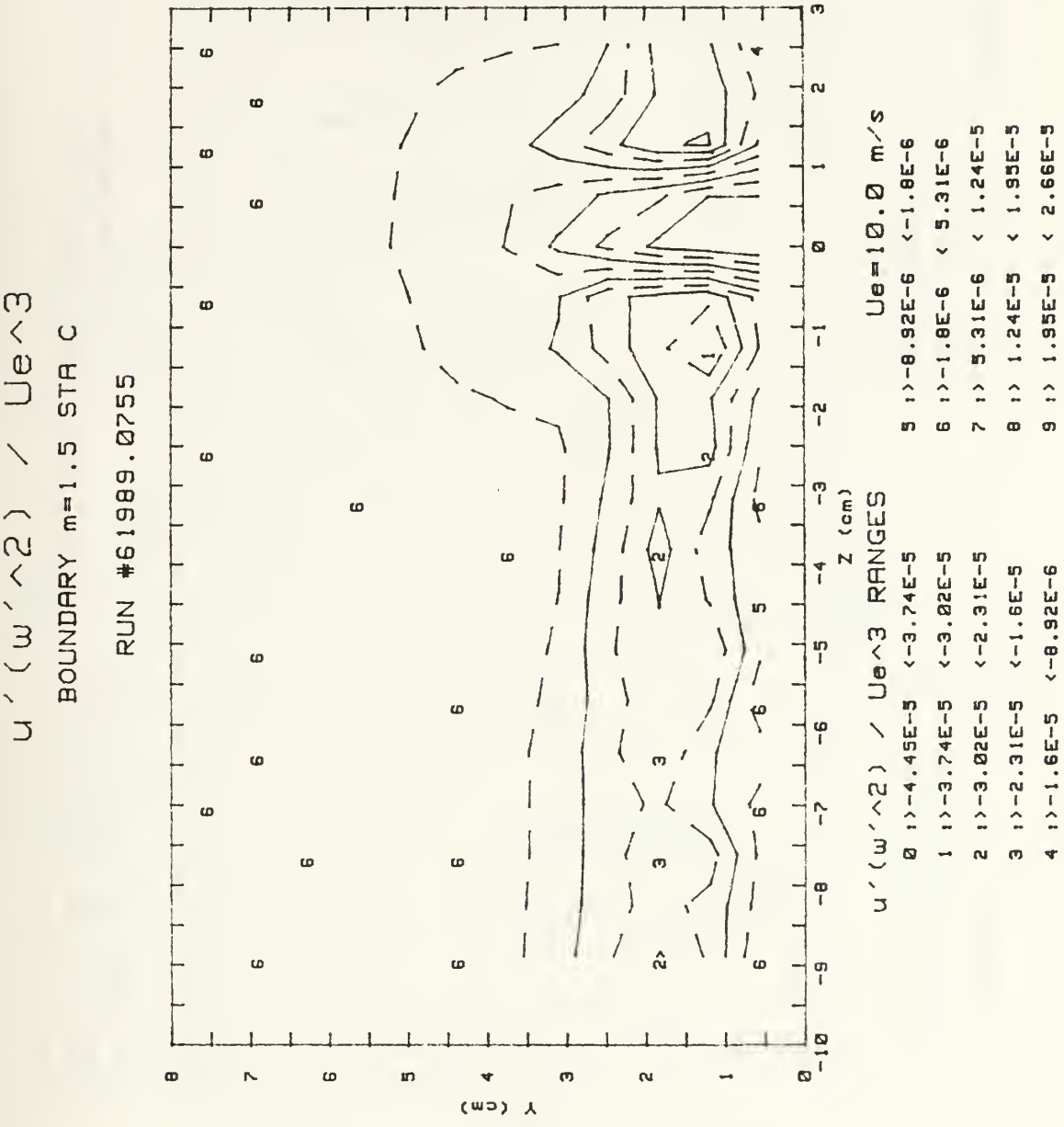

Figure 68. $\overline{u'w'^2}$ (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

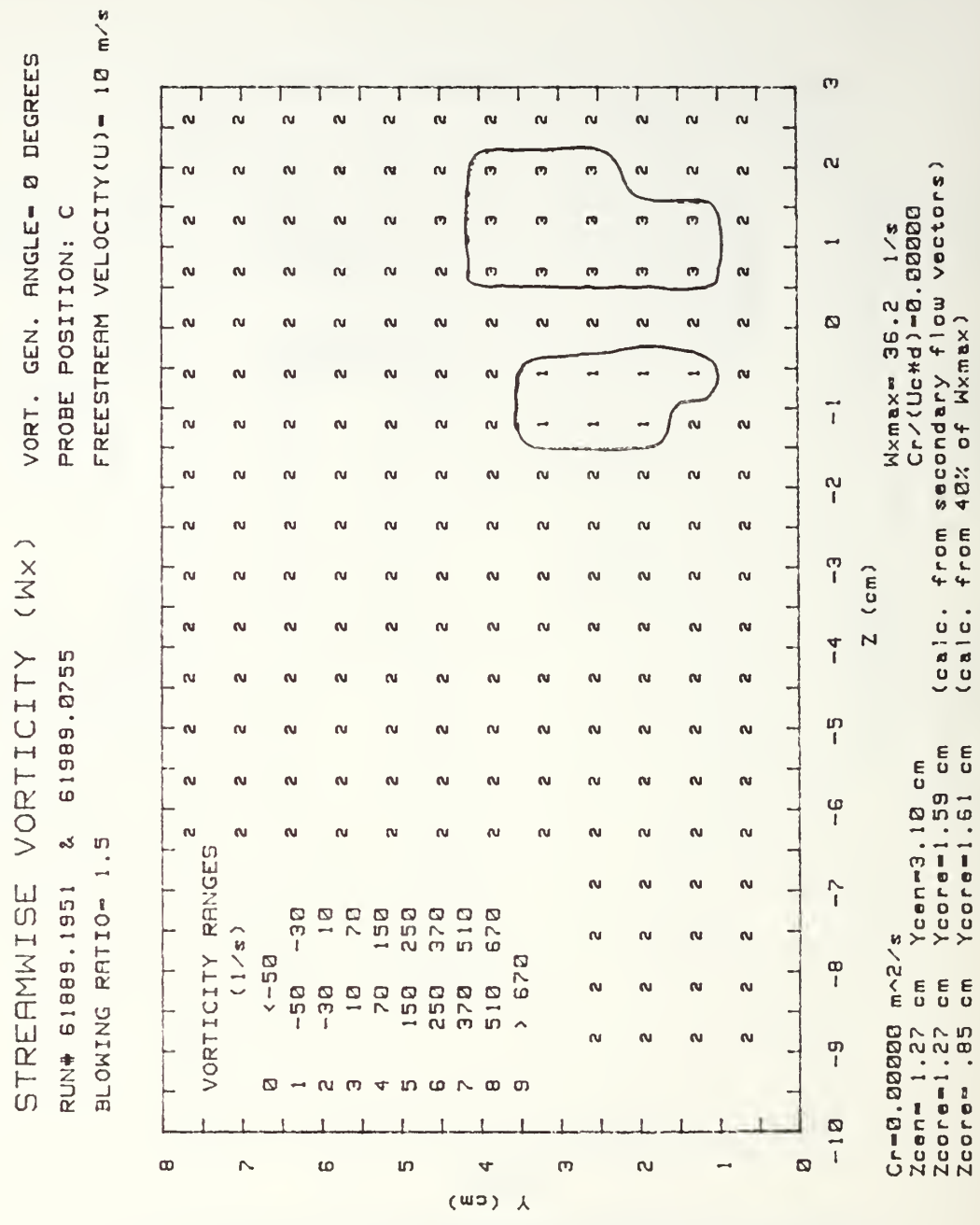

Figure 69. Streamwise Vorticity (Boundary Layer, Station C, m = 1.5, Δ = 0.25)

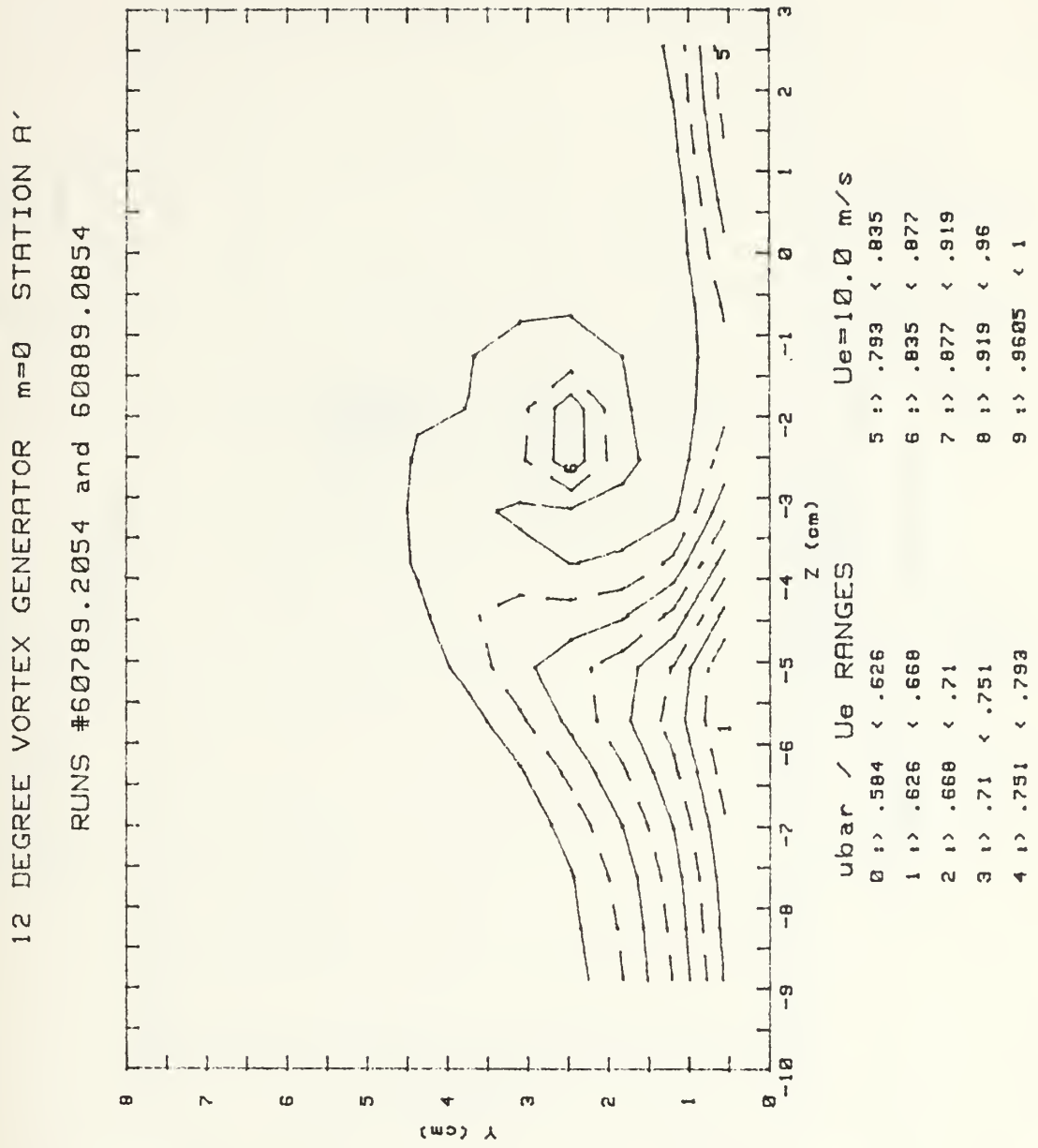

Figure 70. $\bar{u}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

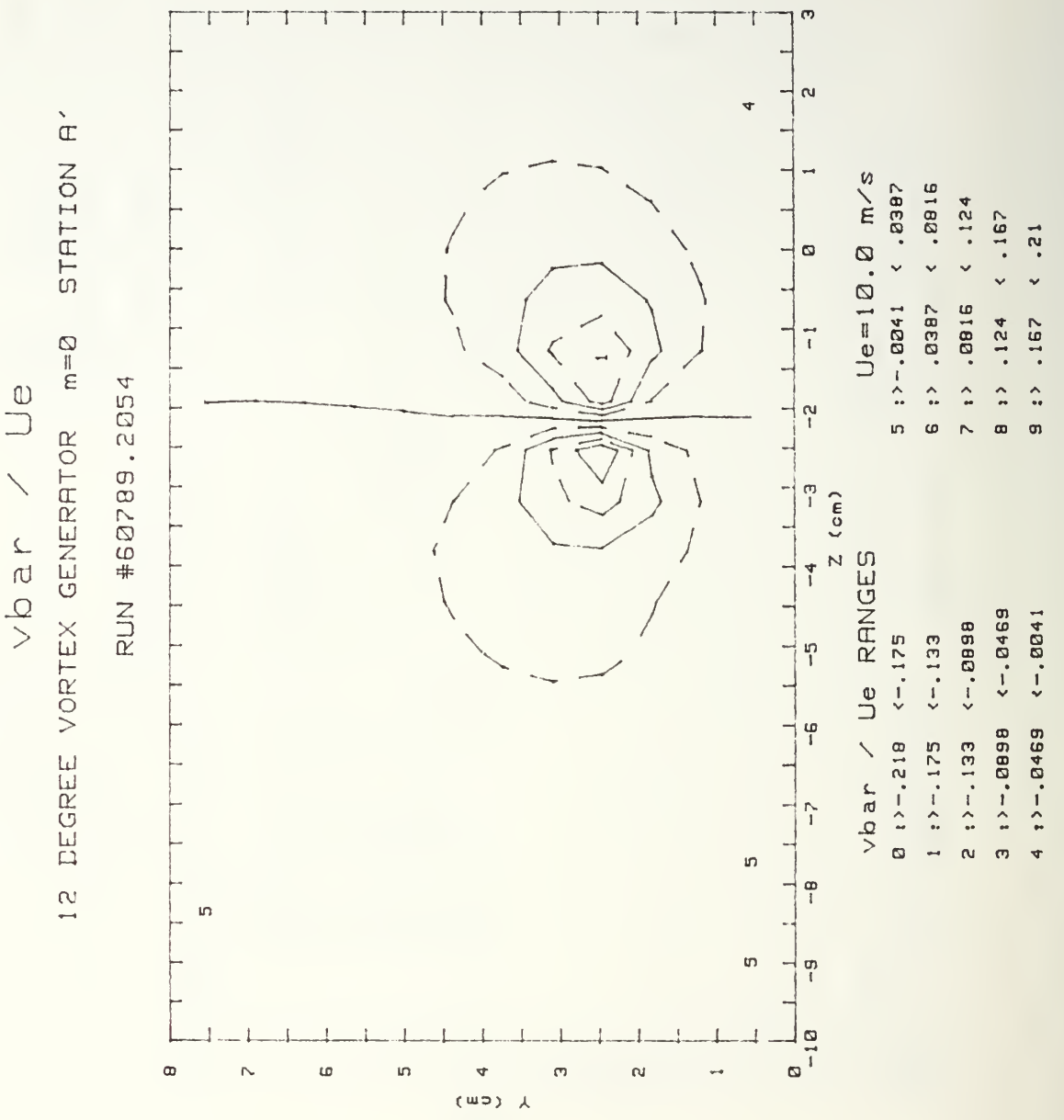

Figure 71. $\bar{v}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

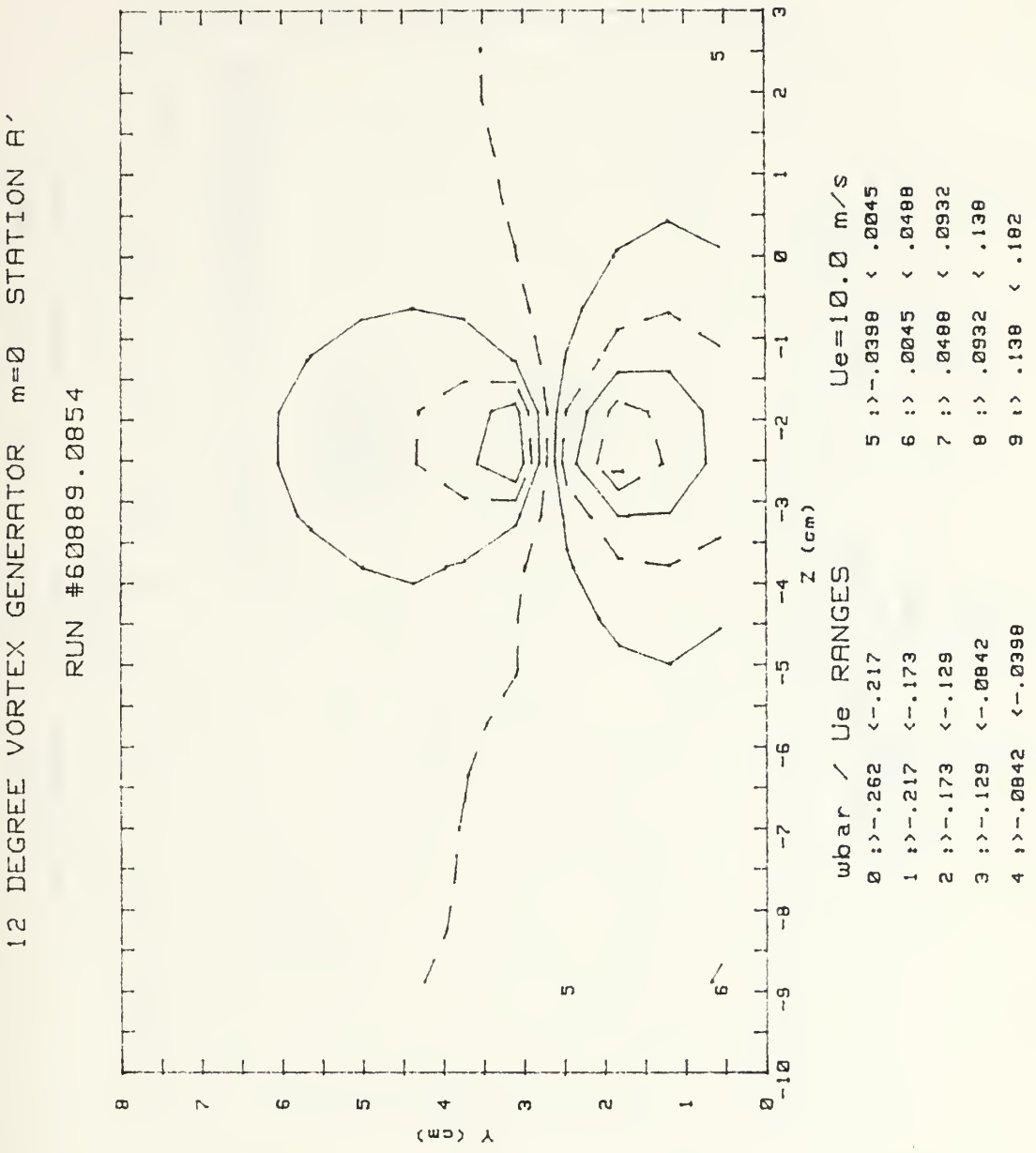

Figure 72. $\overline{w}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', Δ = 0.25)

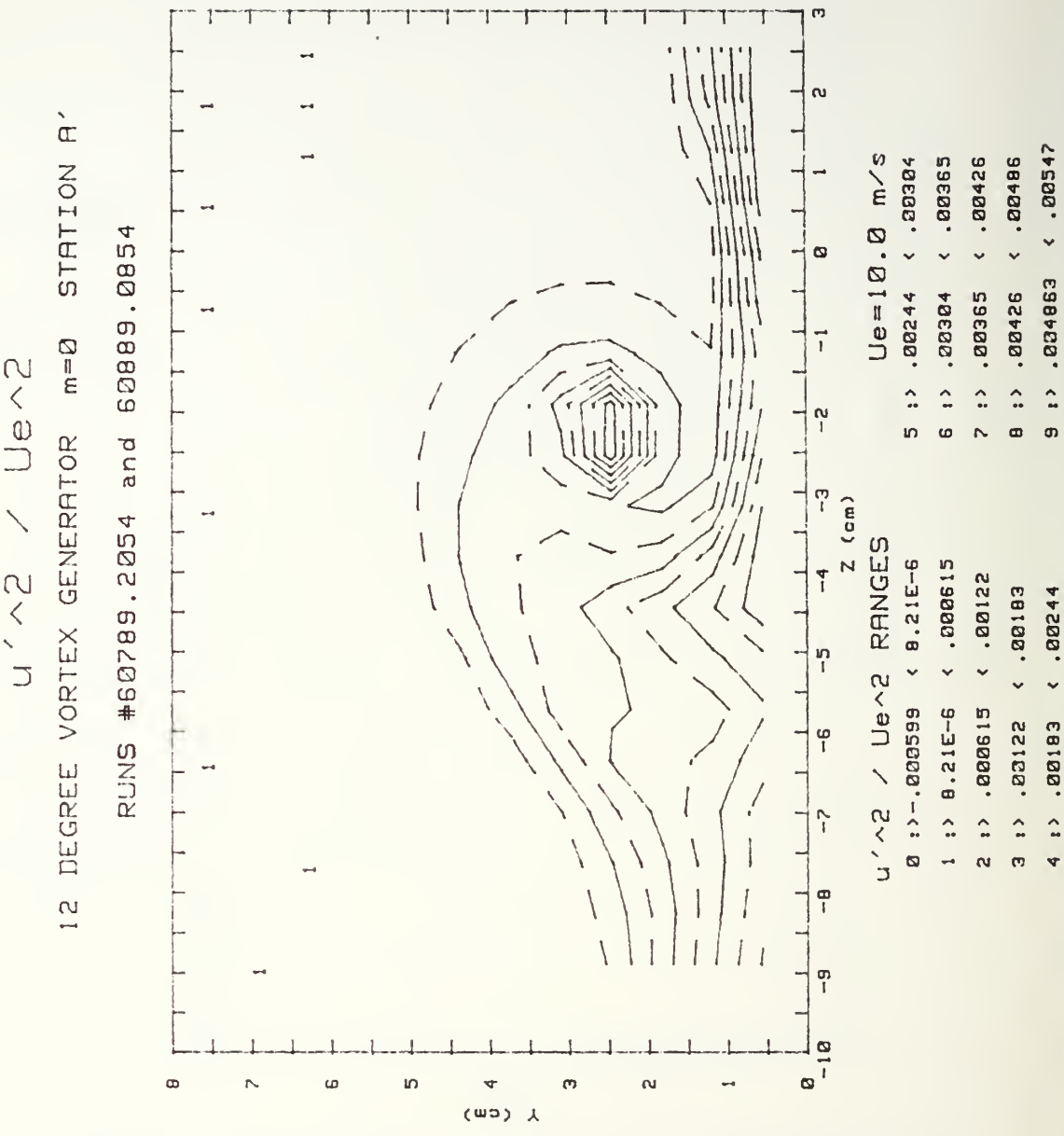

Figure 73. $\overline{u'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

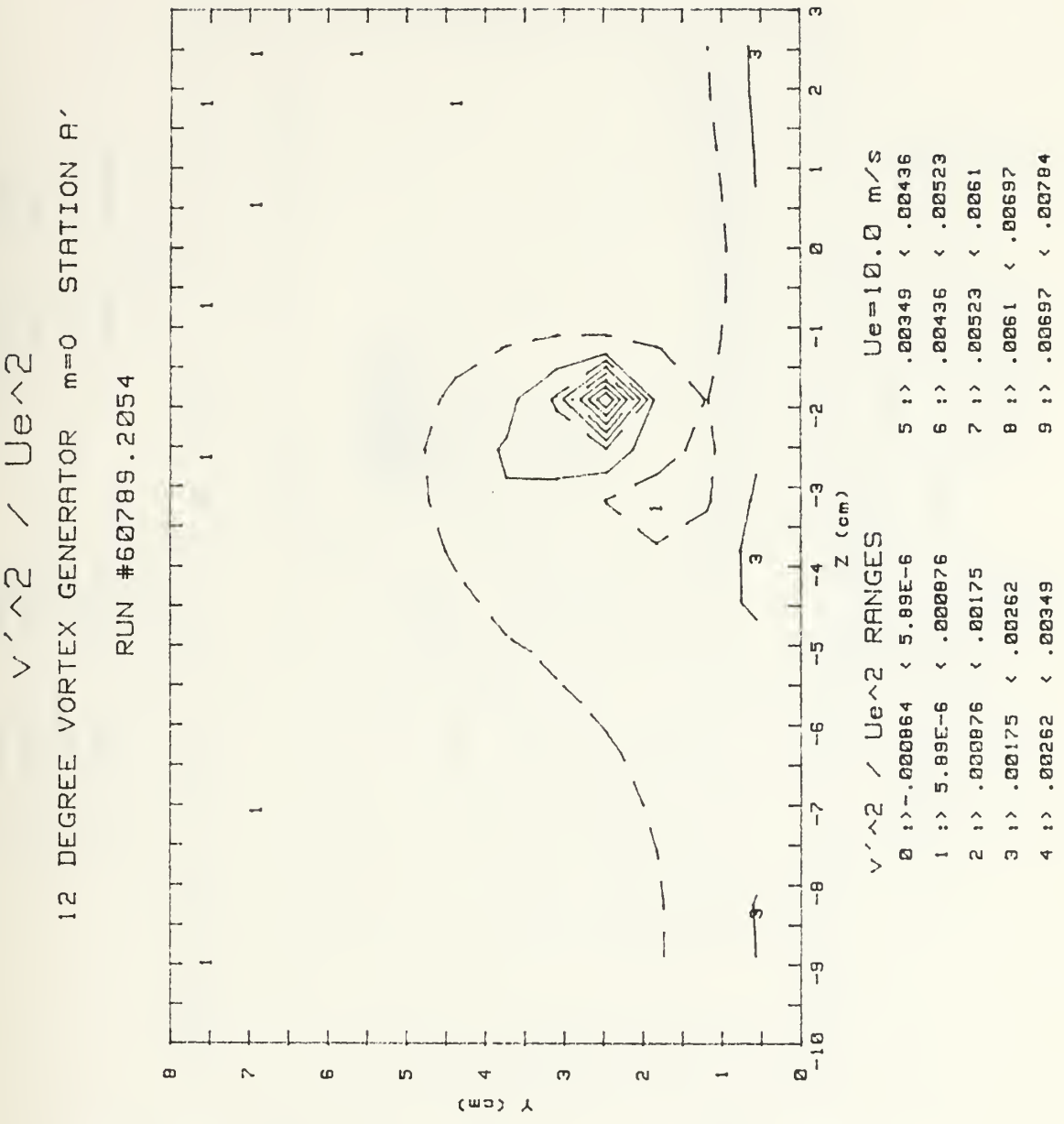

Figure 74. $\overline{v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

Figure 75. $\overline{w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

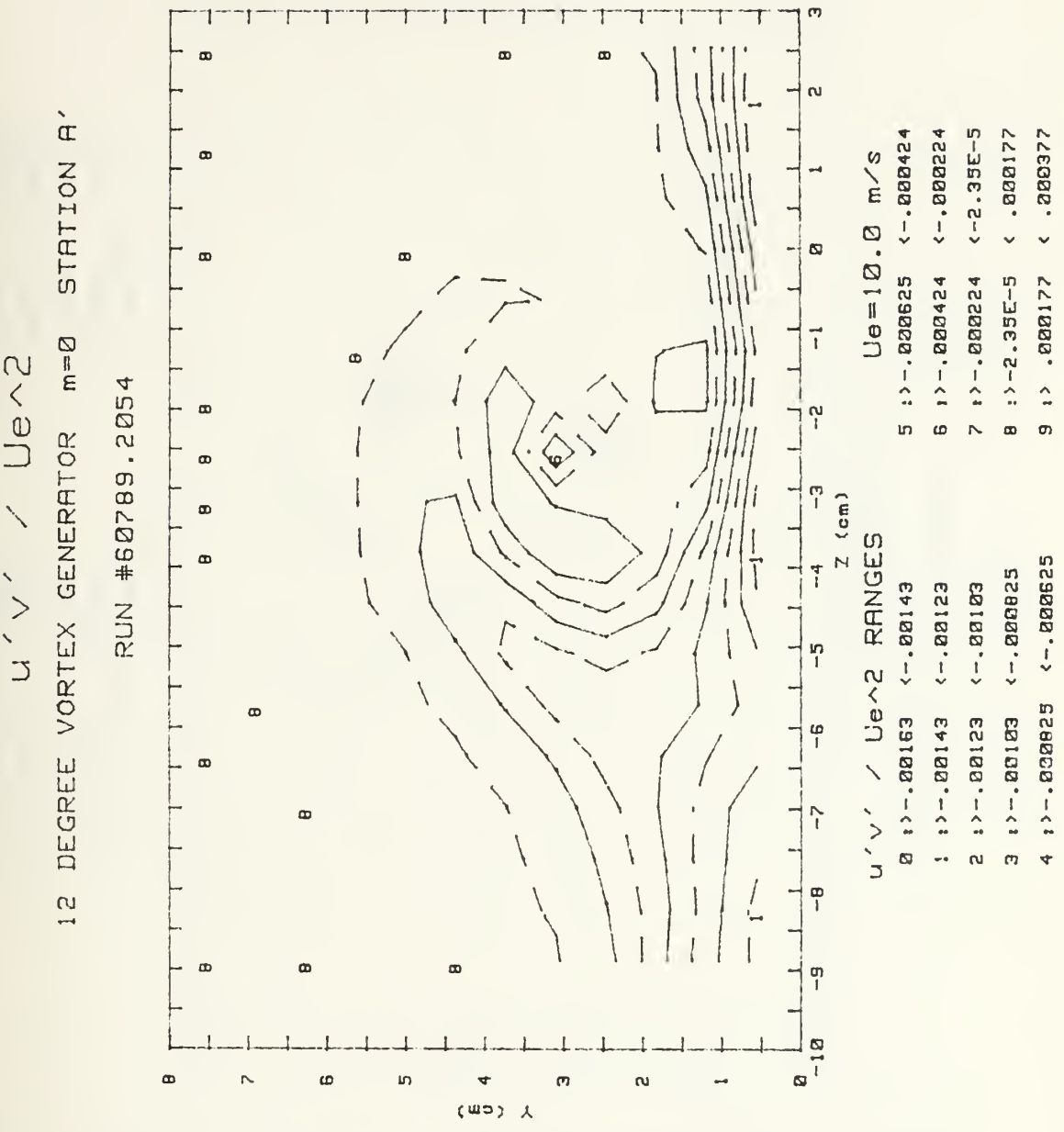

Figure 76. $\overline{u'v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

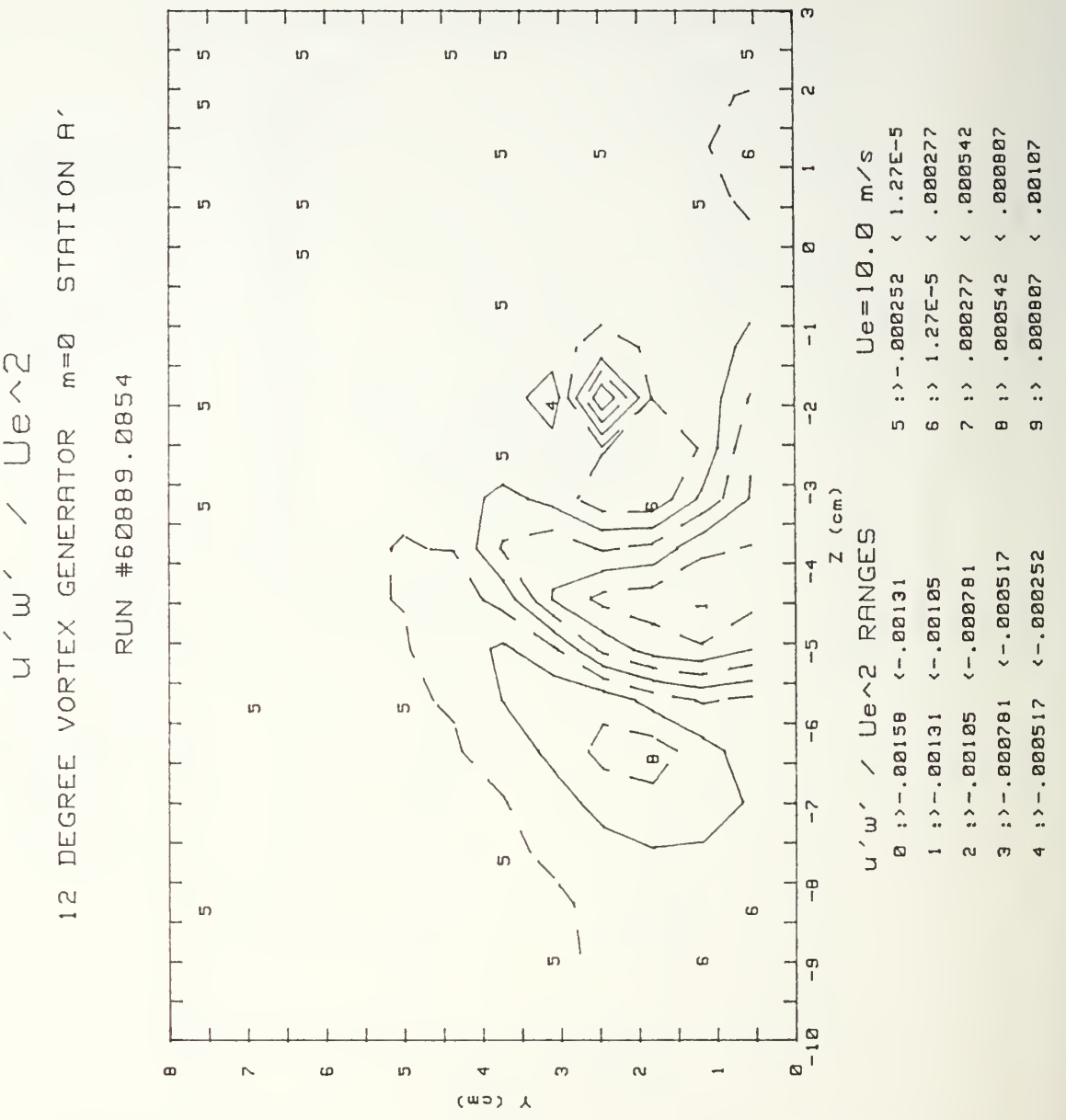

Figure 77. $\overline{u'w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

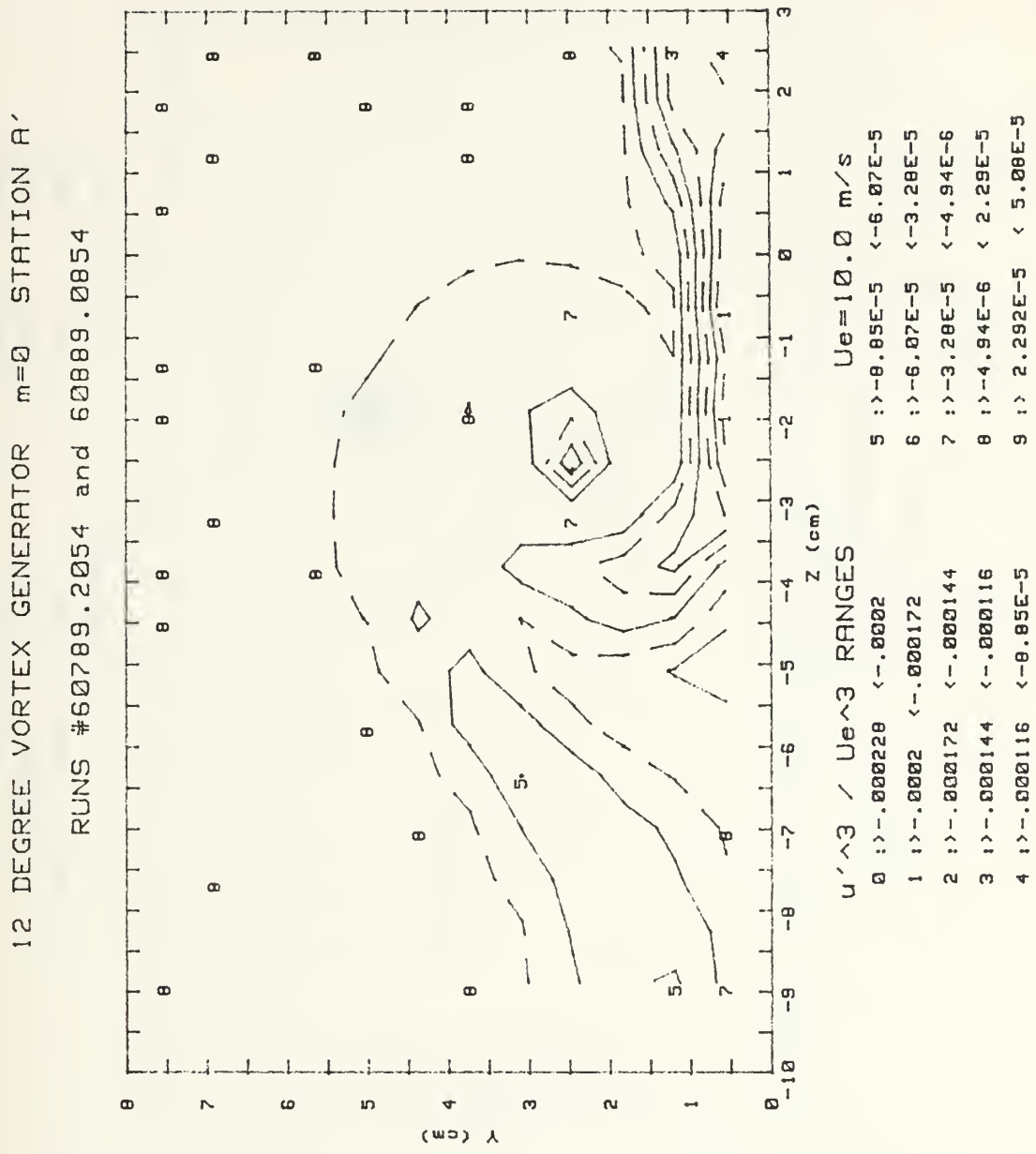

Figure 78. $\overline{u'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

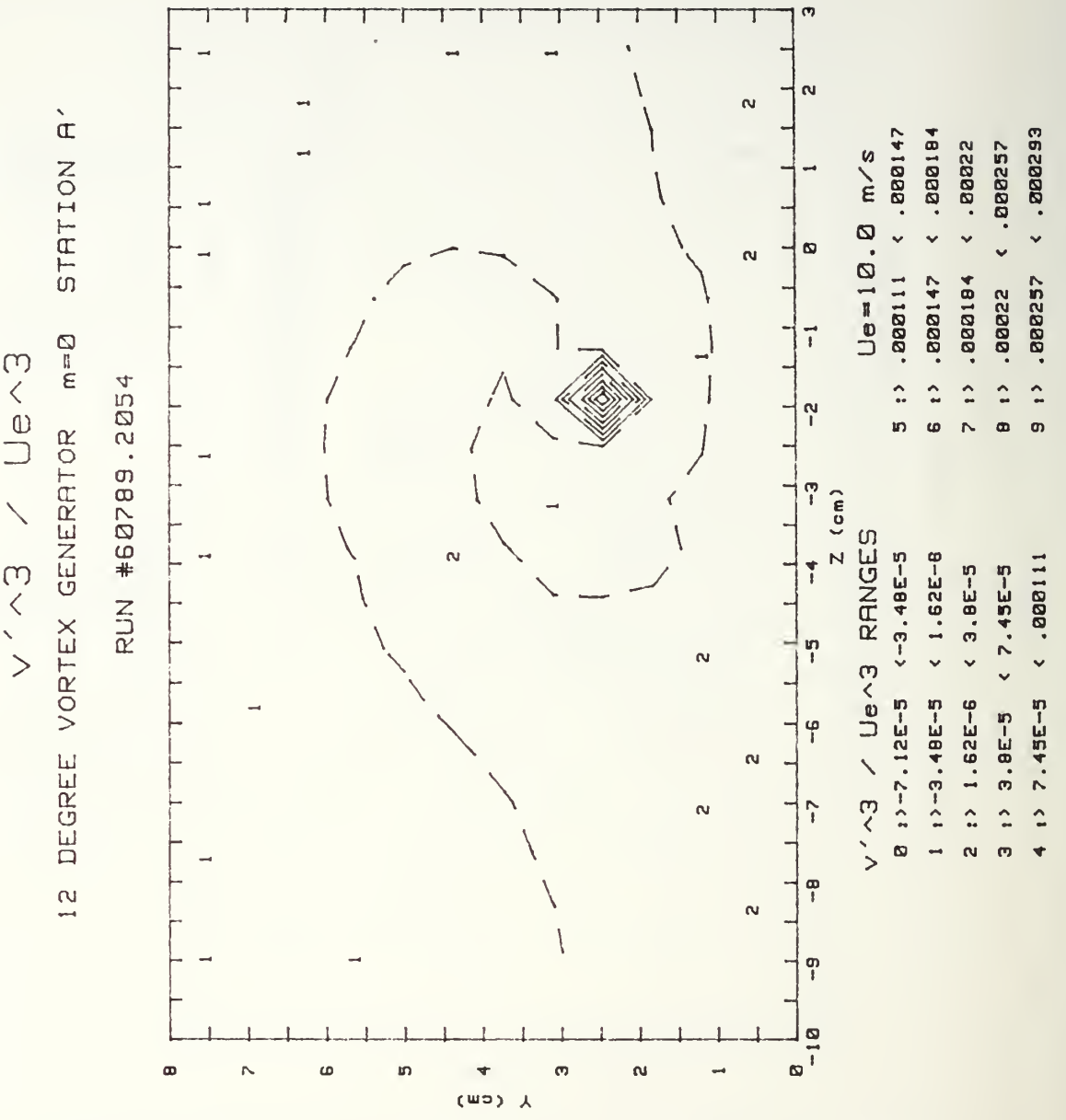

Figure 79. $\overline{v'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

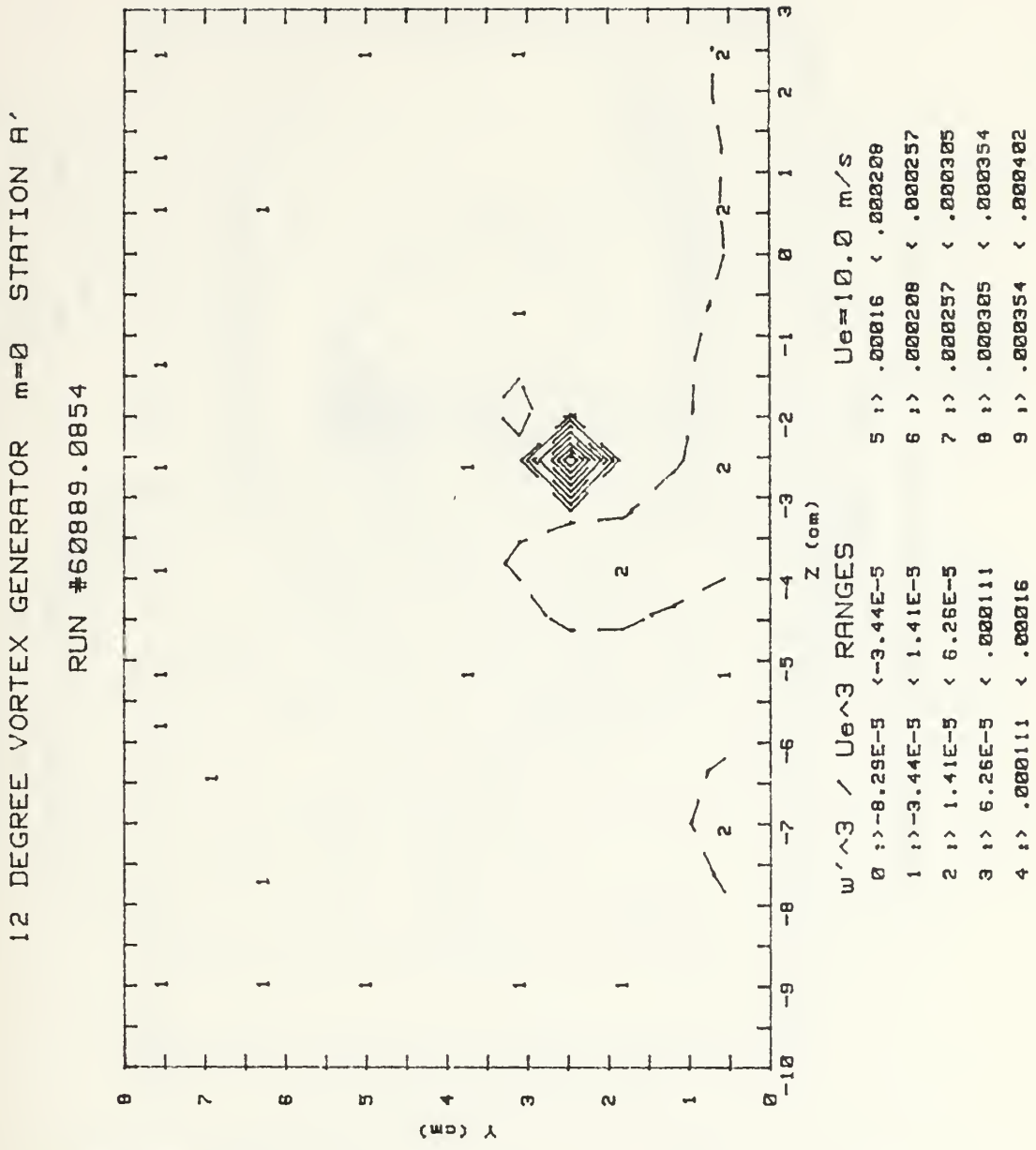

Figure 80. $\overline{w'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

Figure 81. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

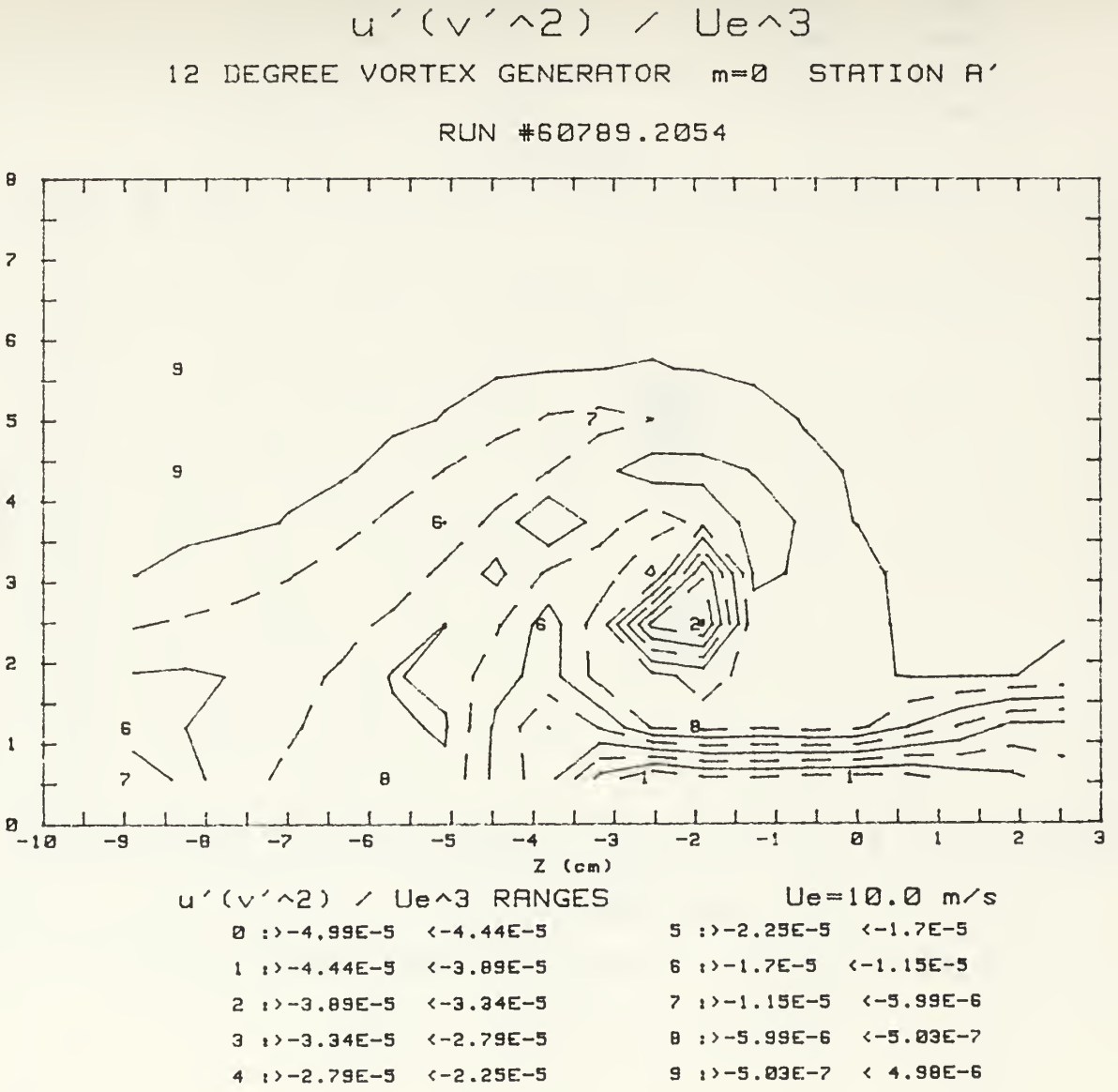

Figure 82. $\overline{u'v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

Figure 83. $\overline{u'^2w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ= 0.25)

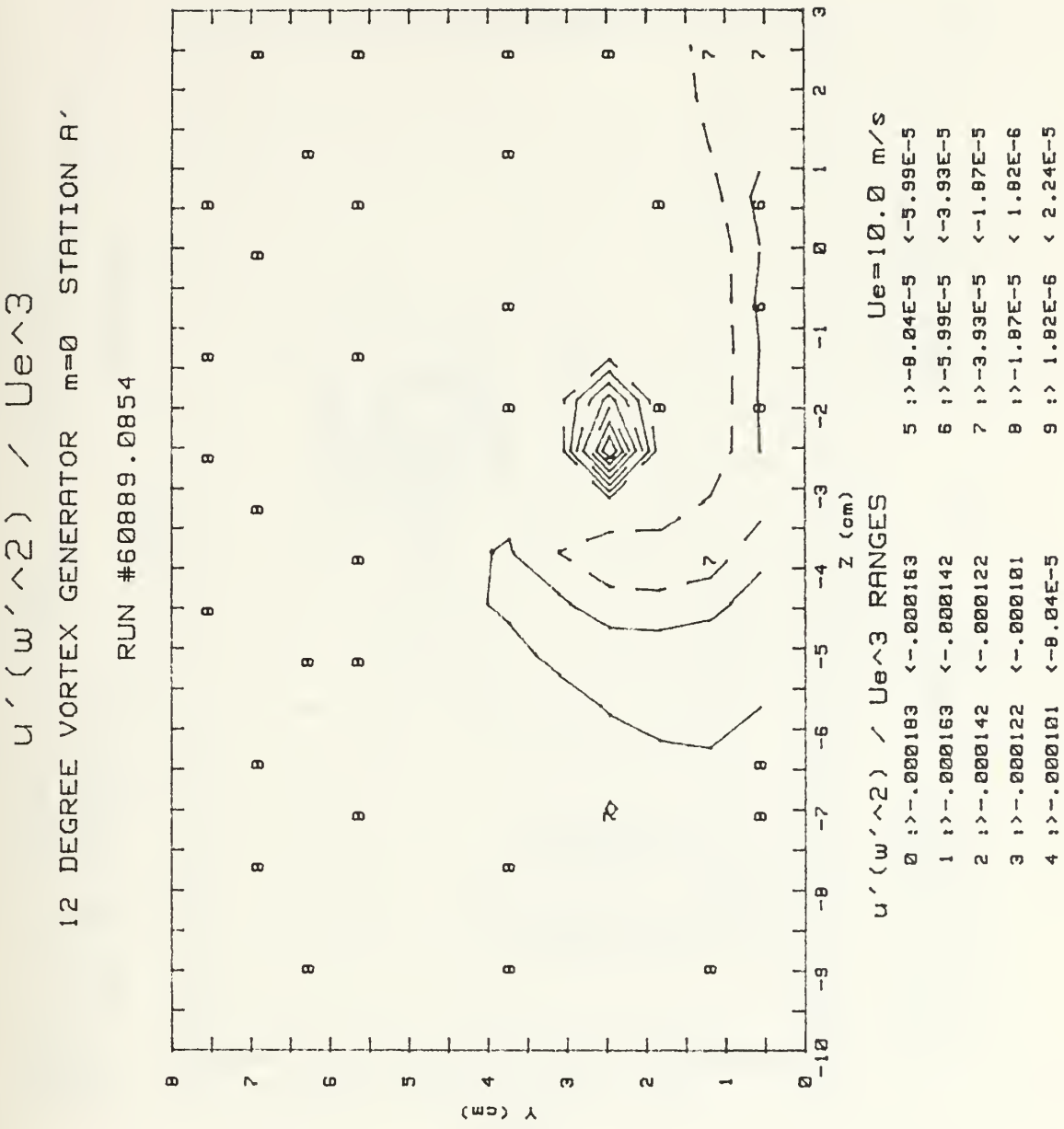

Figure 84. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

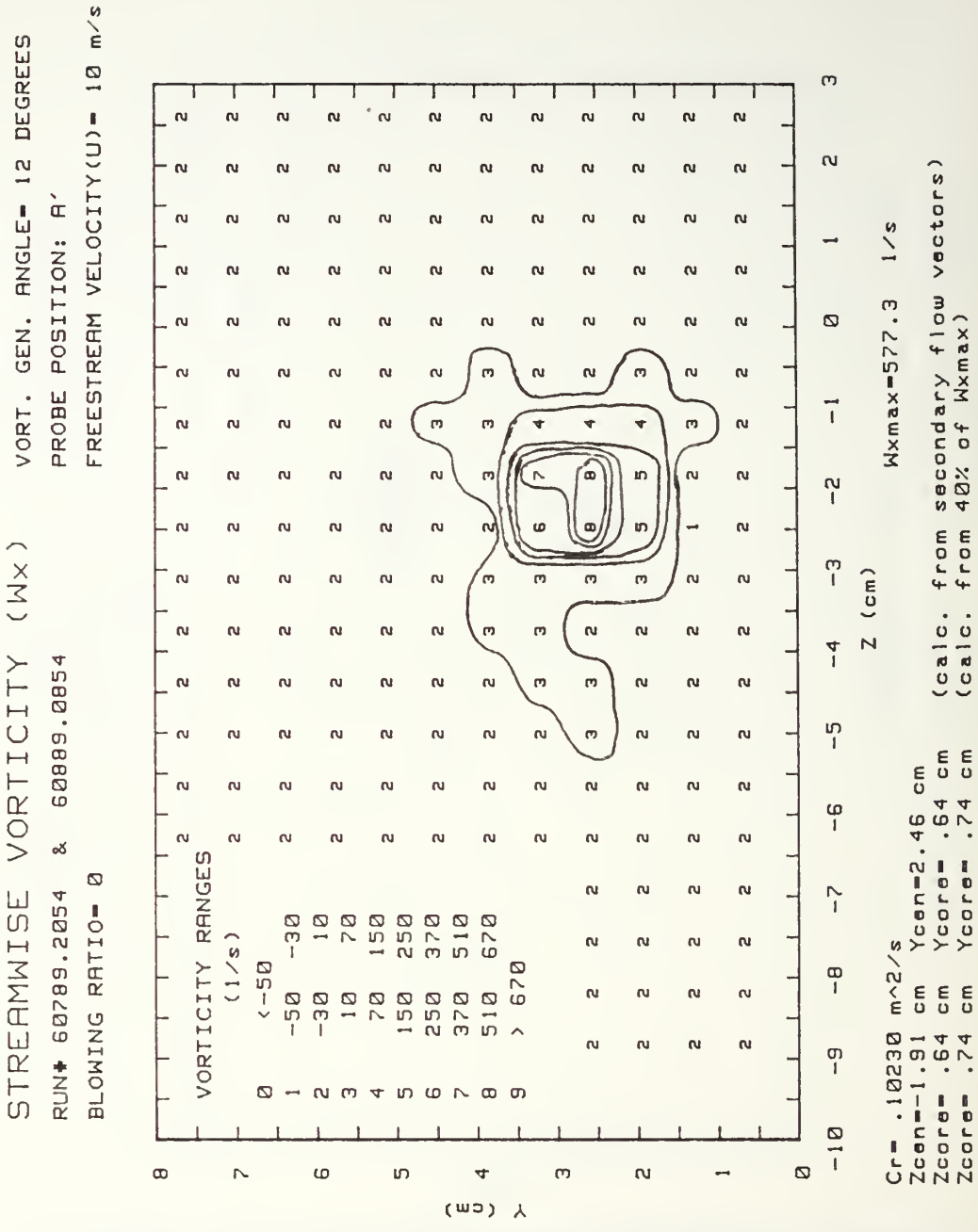

Figure 85. Streamwise Vorticity (Boundary Layer w/vortex, Downwash @ Centerline, Station A', m = 0, Δ = 0.25)

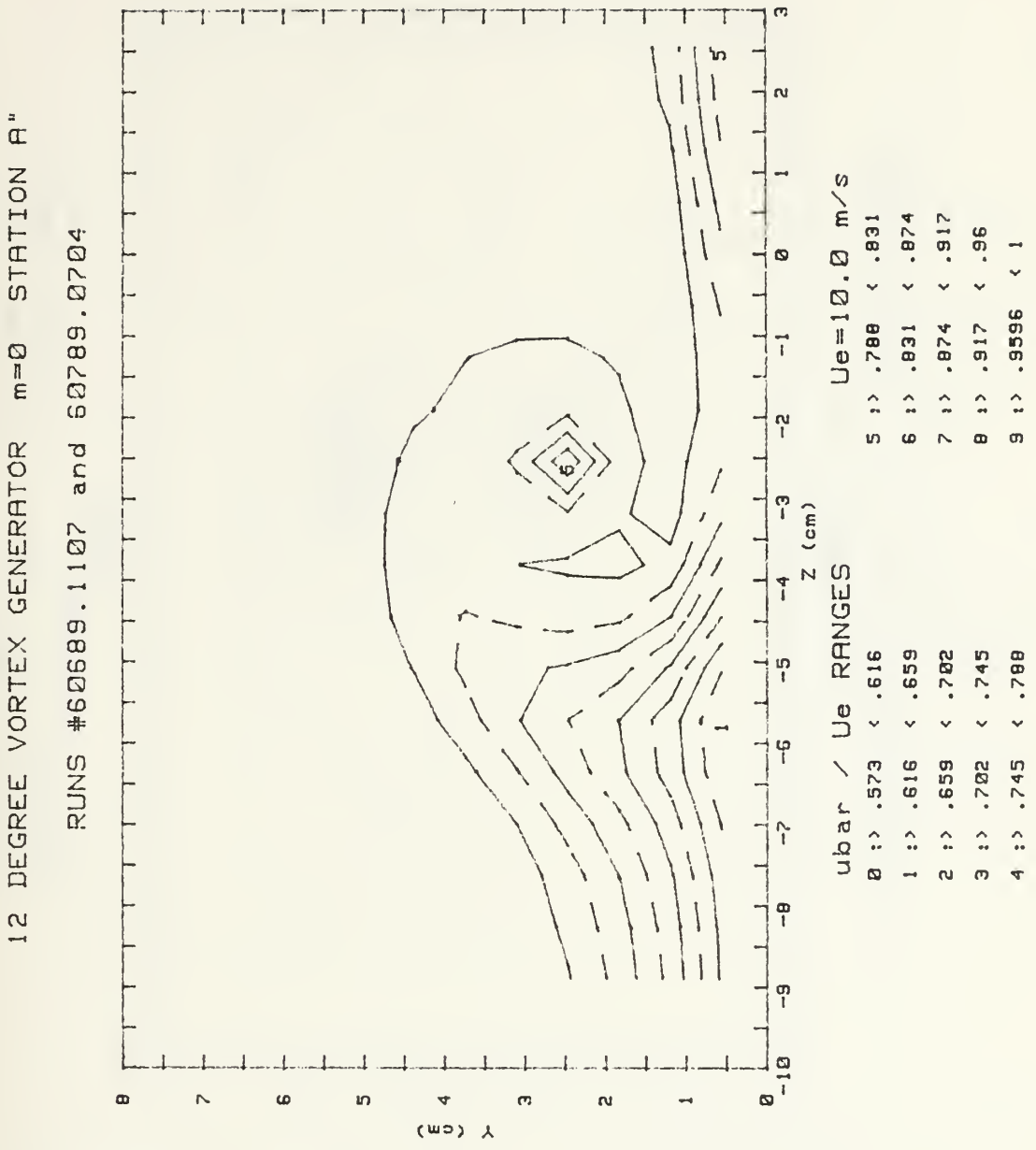

Figure 86. $\bar{u}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ= 0.25)

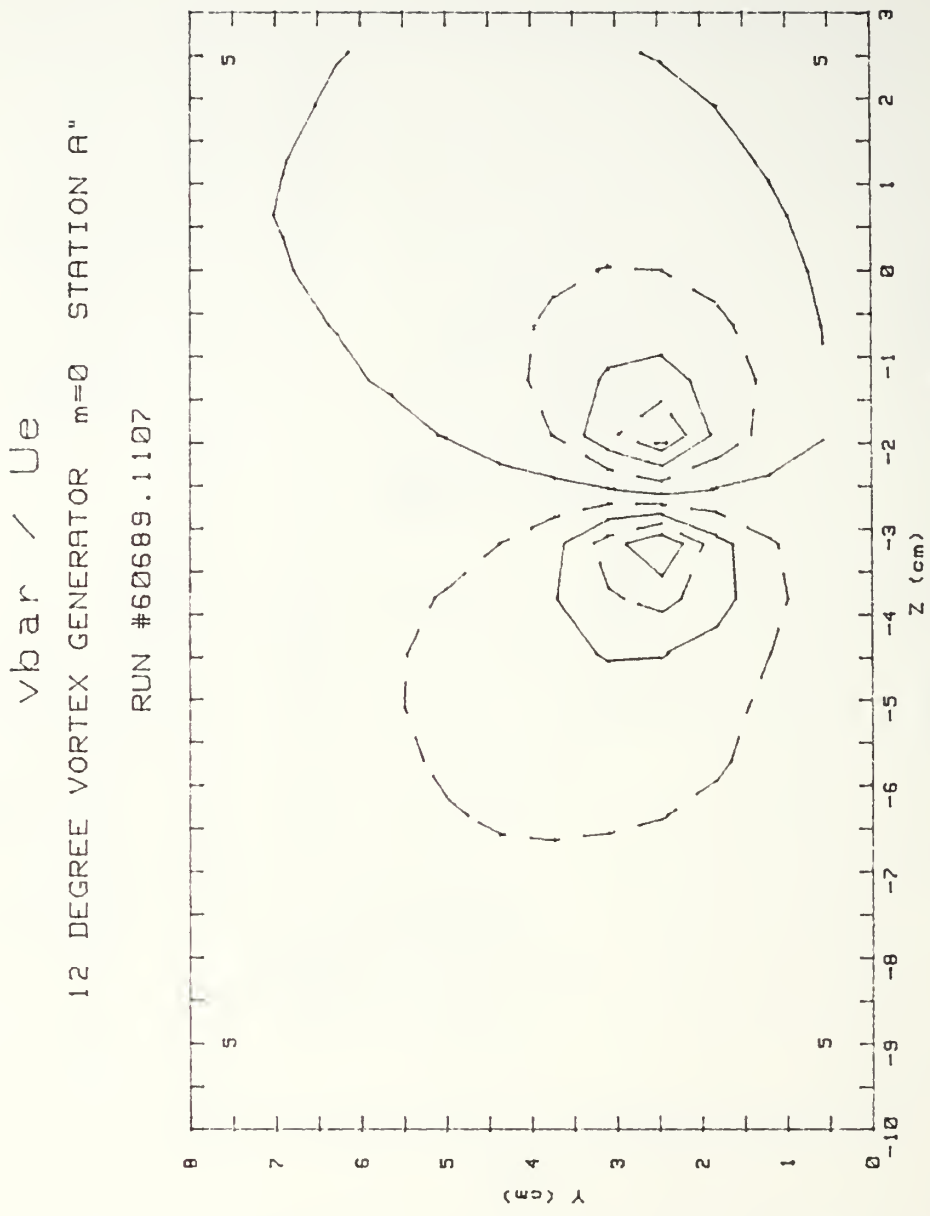

Figure 87. $\bar{v}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

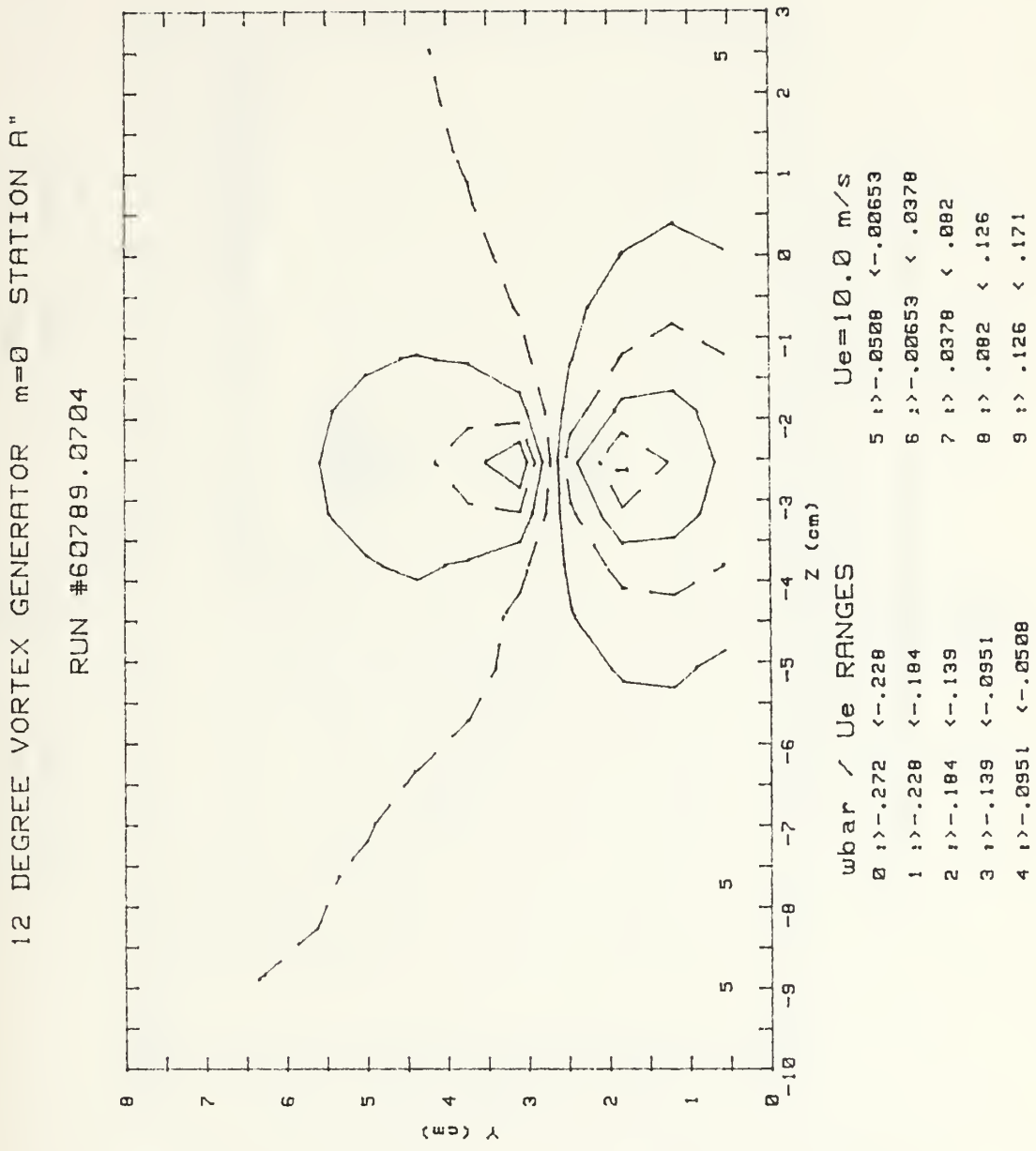

Figure 88. $\overline{w}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

Figure 89. $\overline{u'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

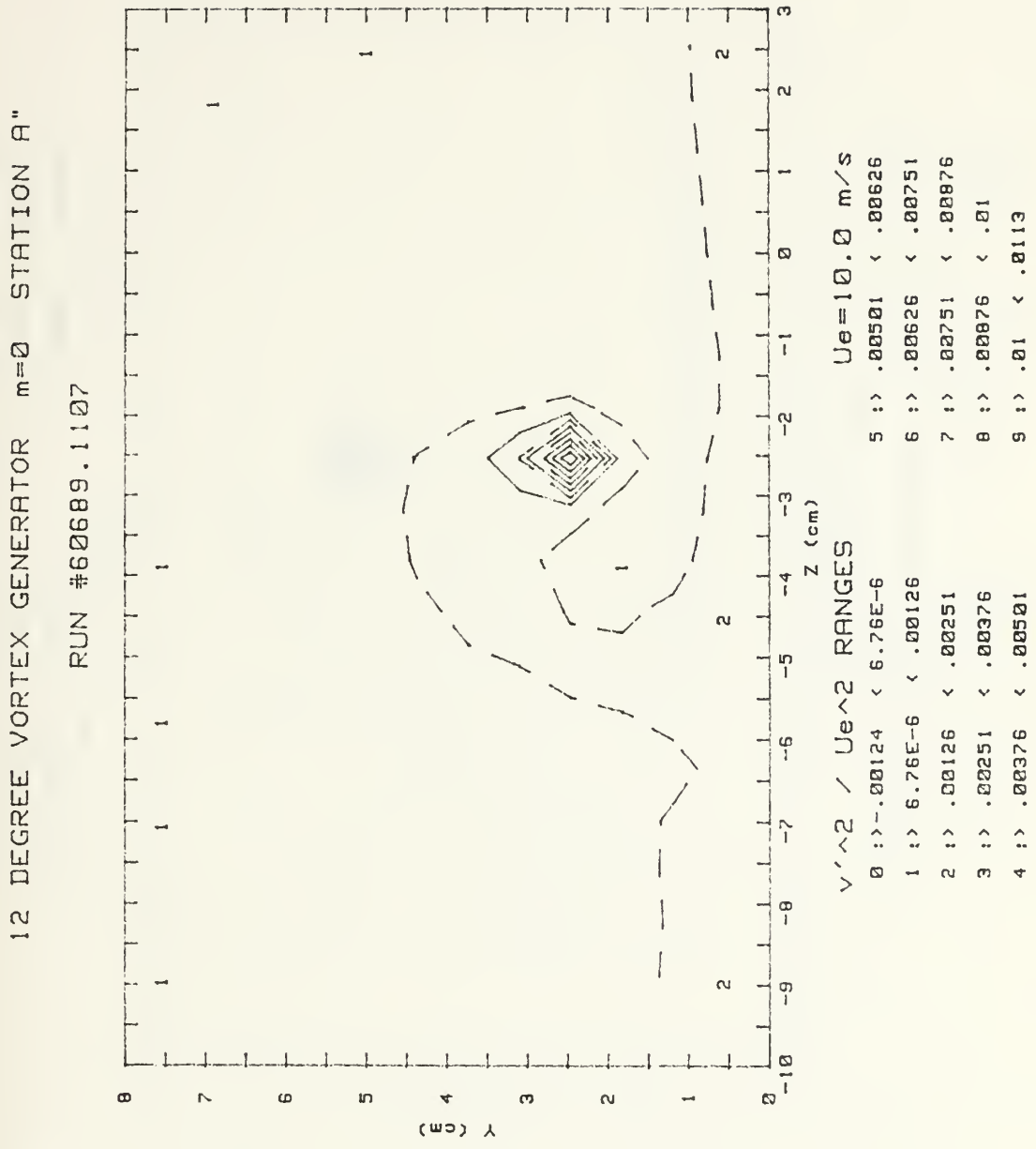

Figure 90. $\overline{v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

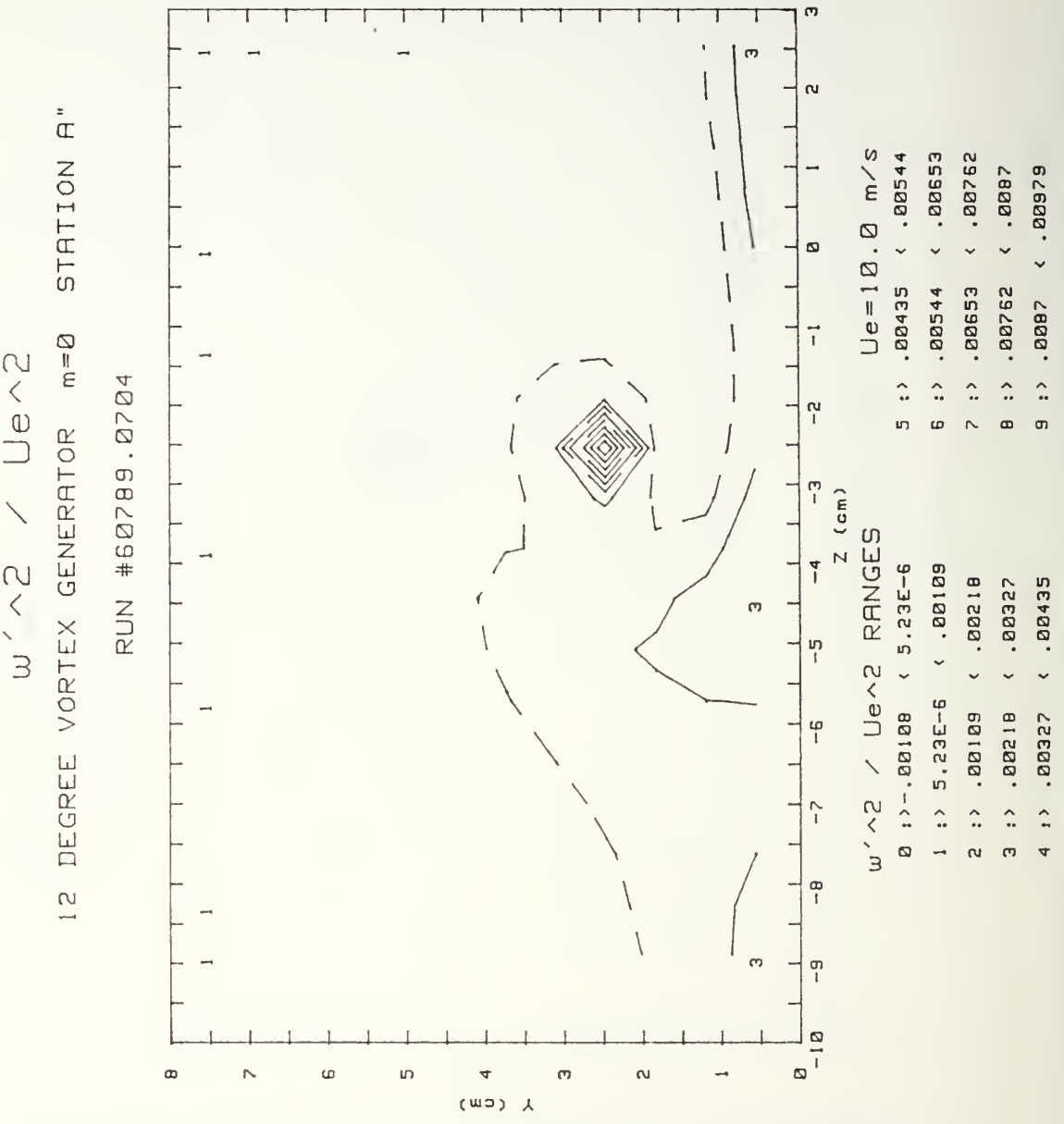

Figure 91. $\overline{w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

Figure 92. $\overline{u'v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

Figure 93. $\overline{u'w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

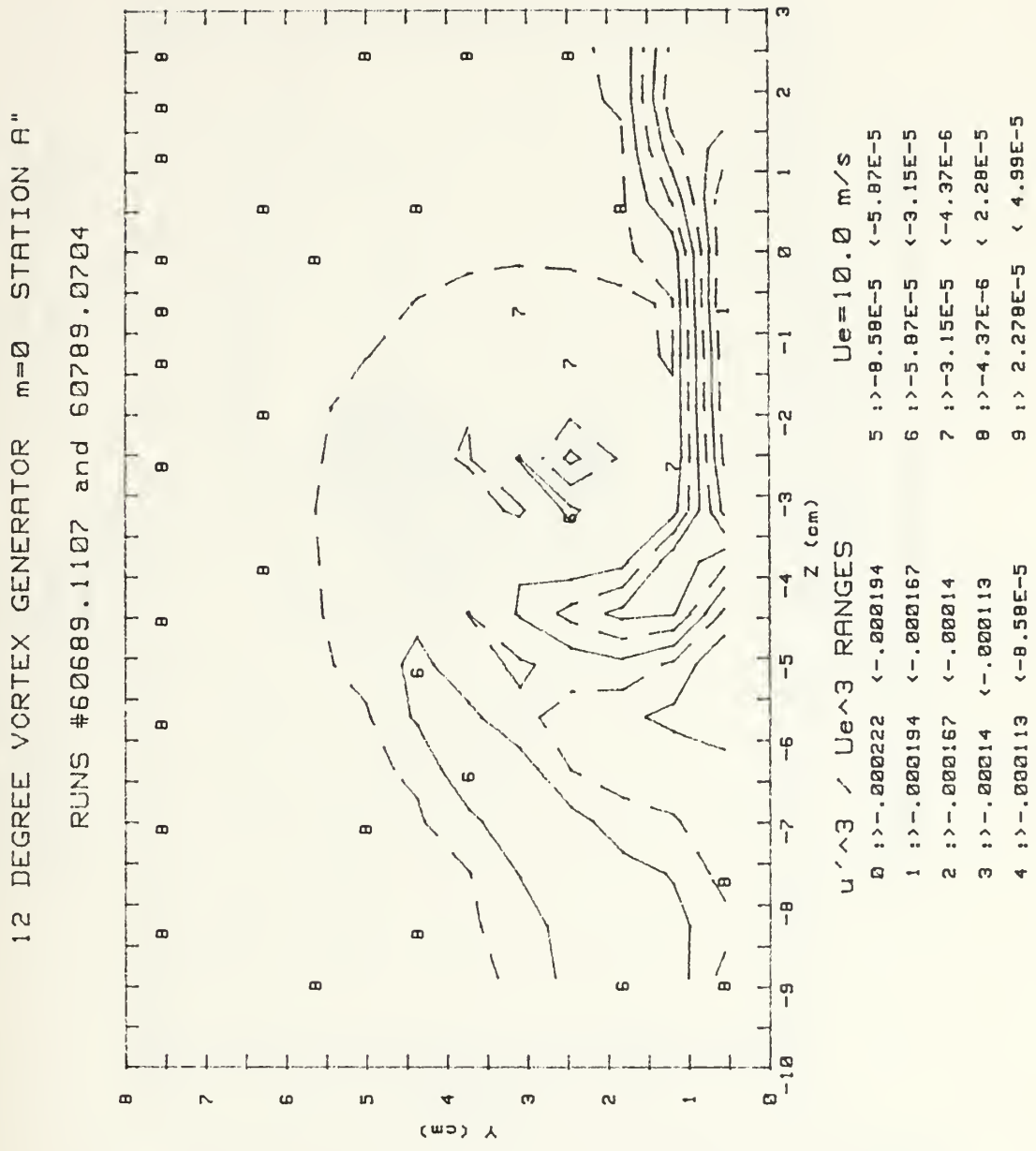

Figure 94. $\overline{u'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

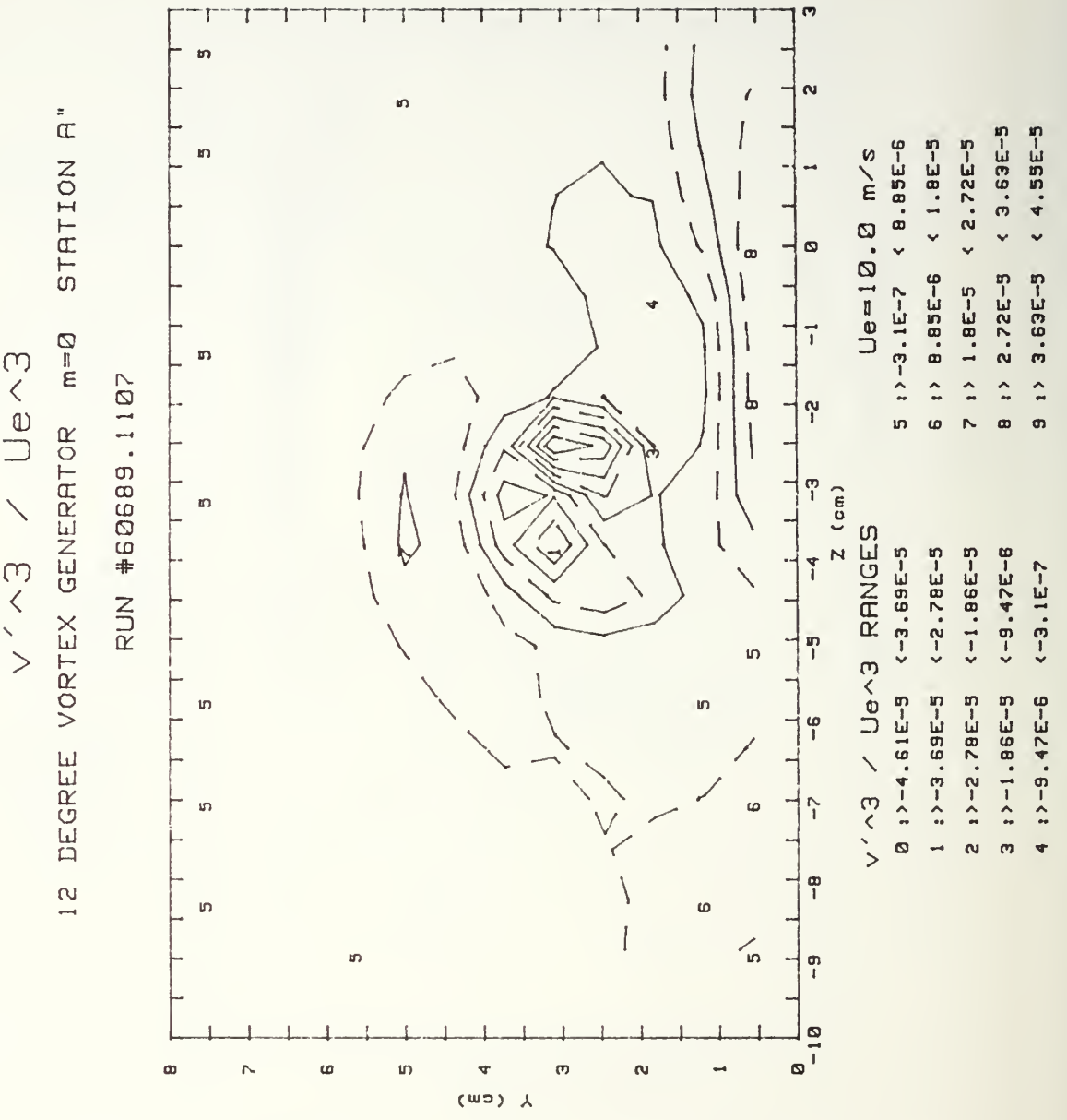

Figure 95. $\overline{v'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

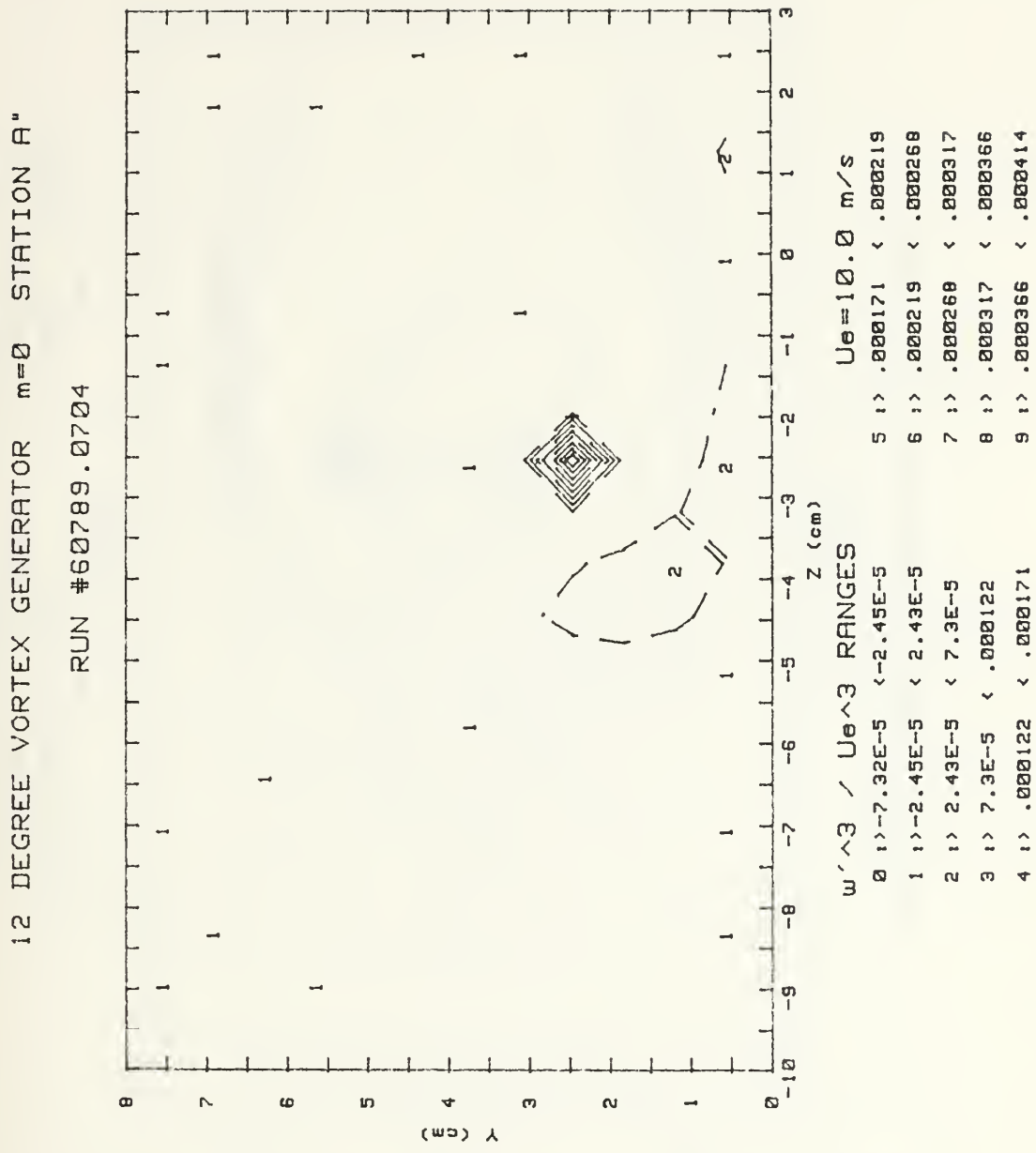

Figure 96. $\overline{w'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

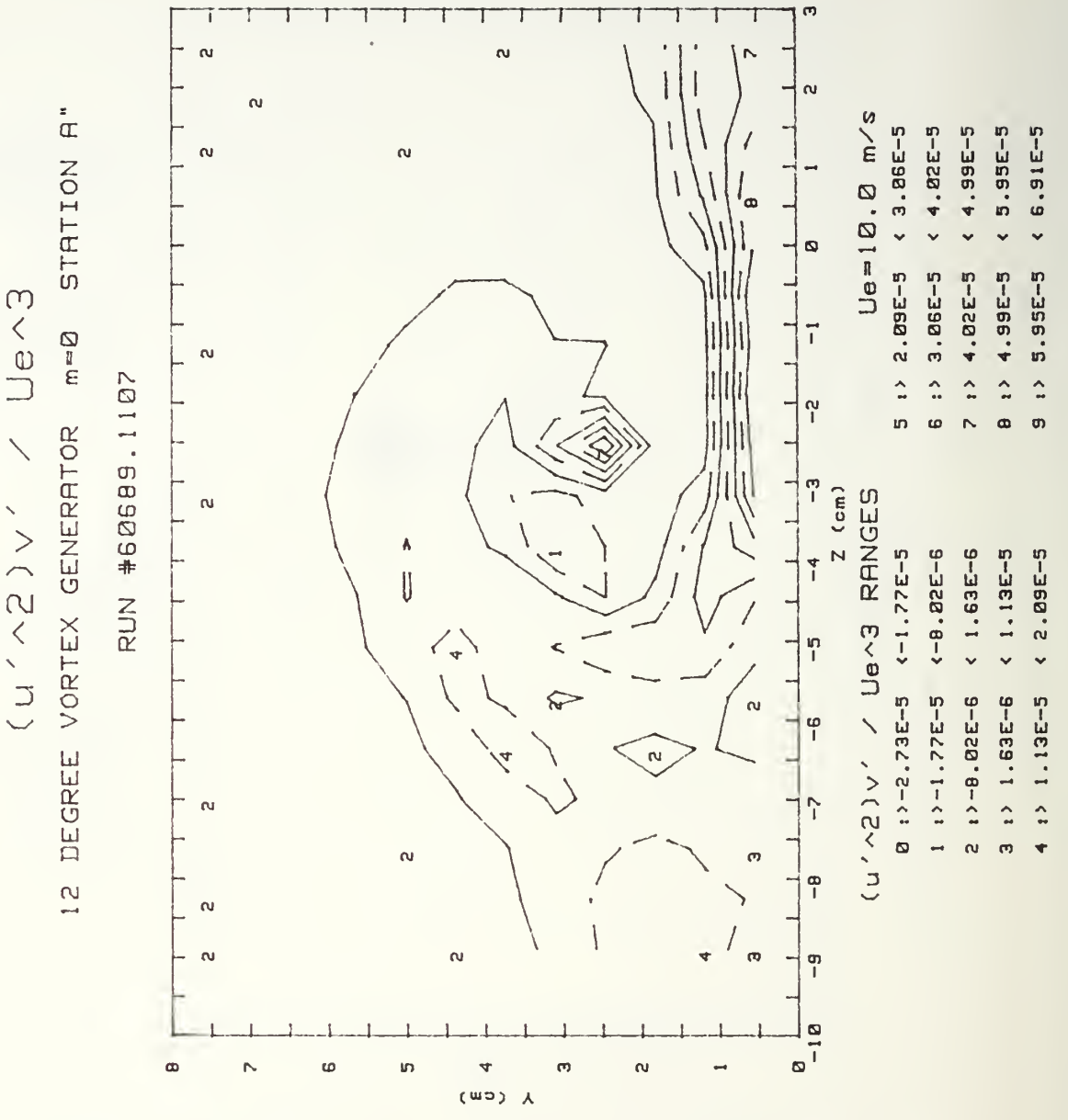

Figure 97. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

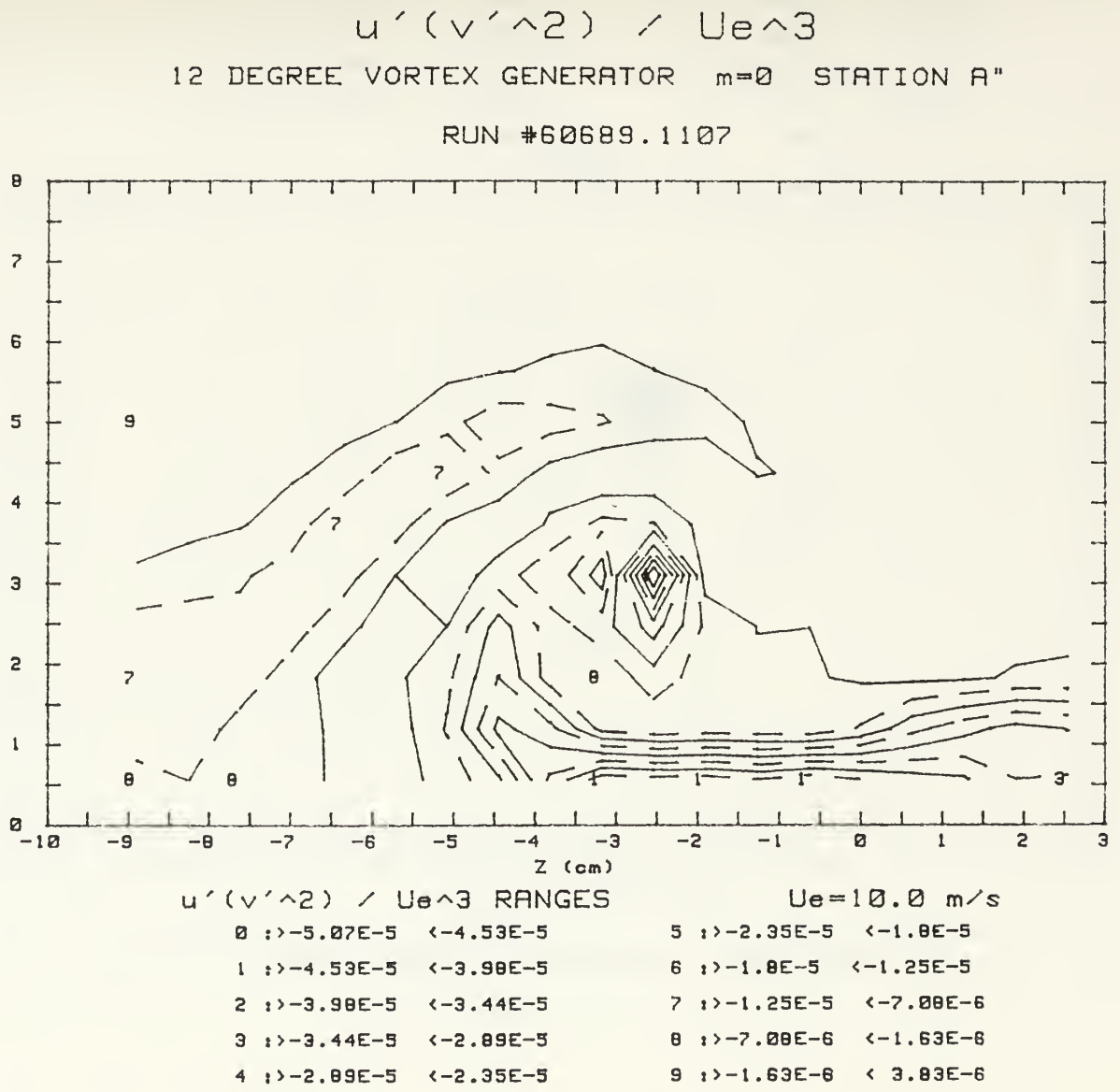

Figure 98. $\overline{u'v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

Figure 99. $\overline{u'^2w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

Figure 100. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', m = 0, Δ = 0.25)

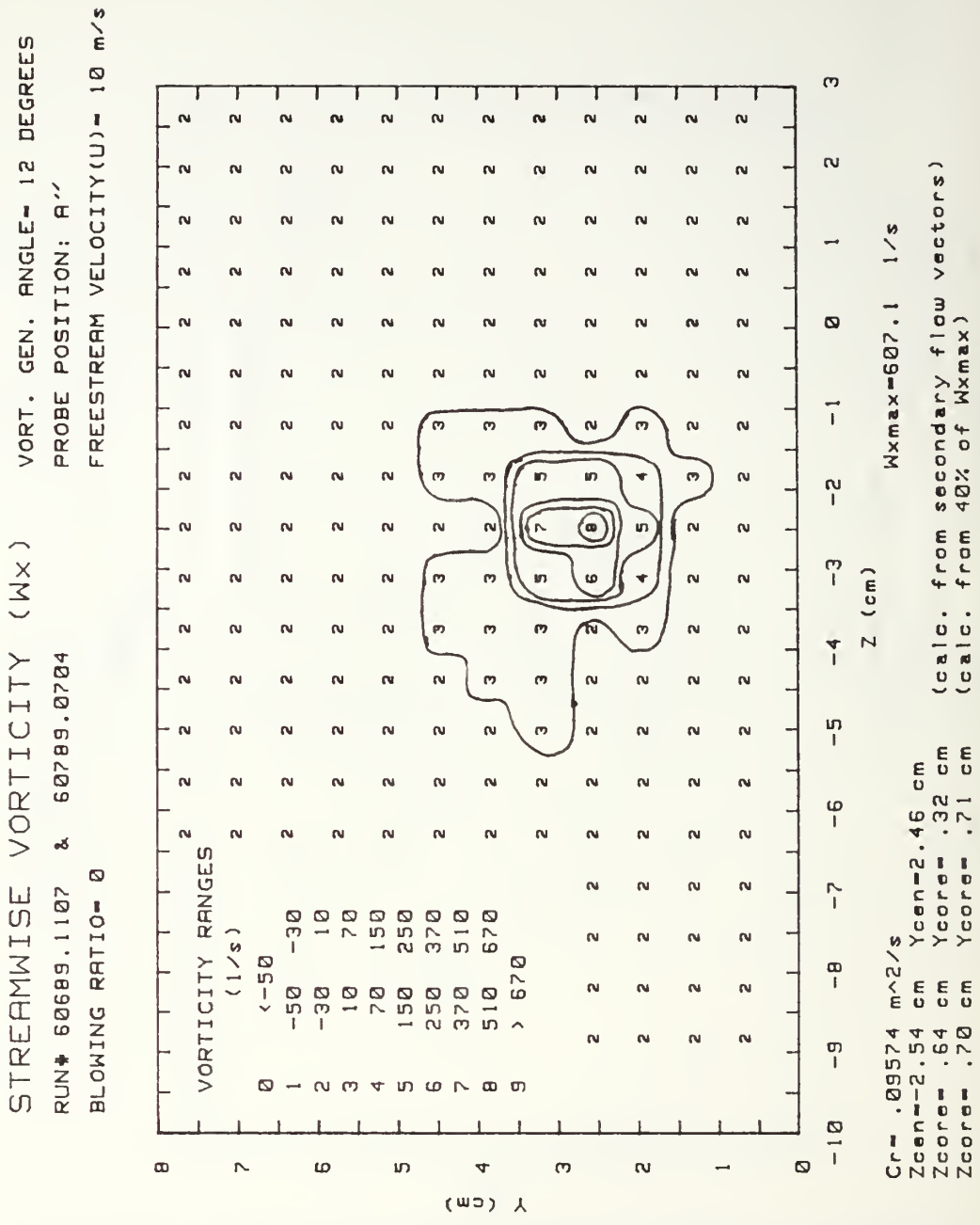

Figure 101. Streamwise Vorticity (Boundary Layer w/vortex, Downwash @ Centerline, Station A'', $m = 0$, $\Delta = 0.25$)

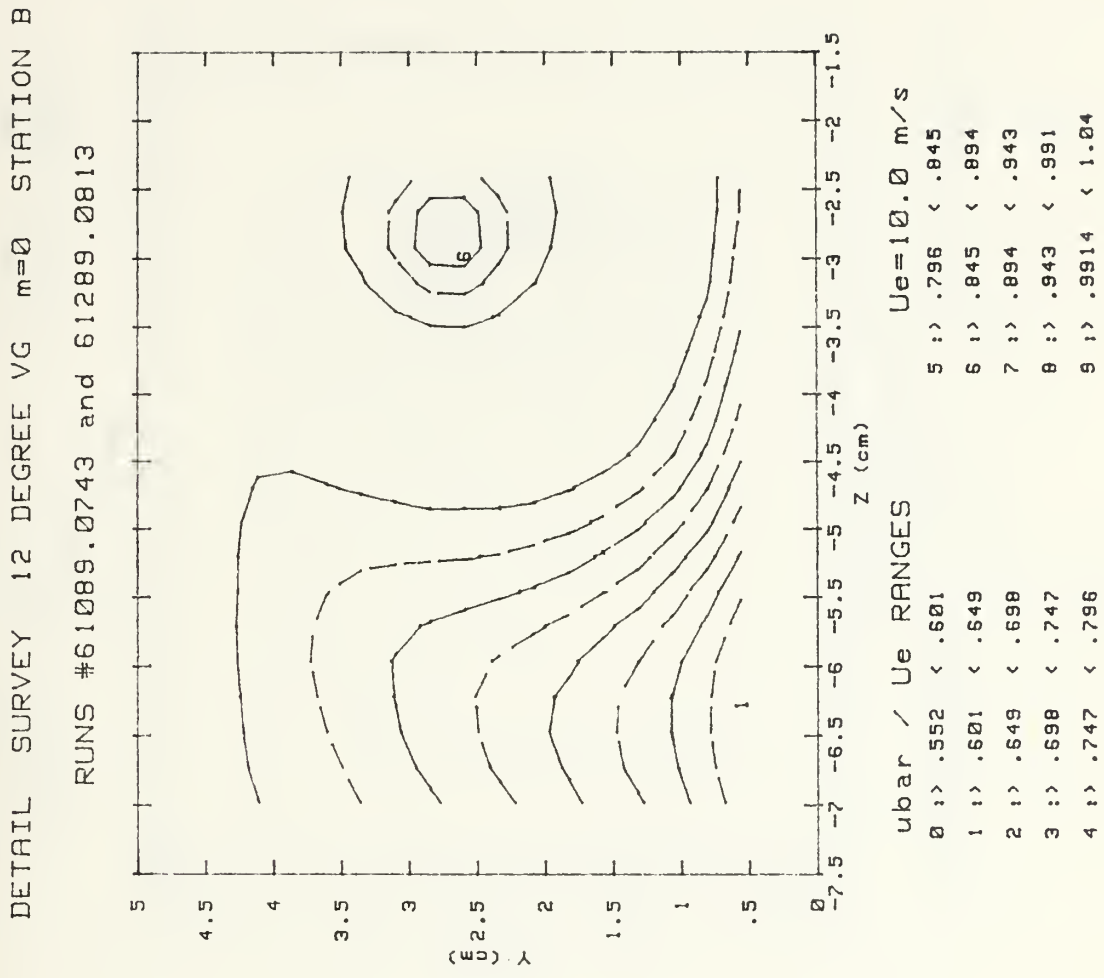

Figure 102. $\bar{u}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

Figure 103. $\bar{v}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ= 0.10)

Figure 104. $\overline{w}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ= 0.10)

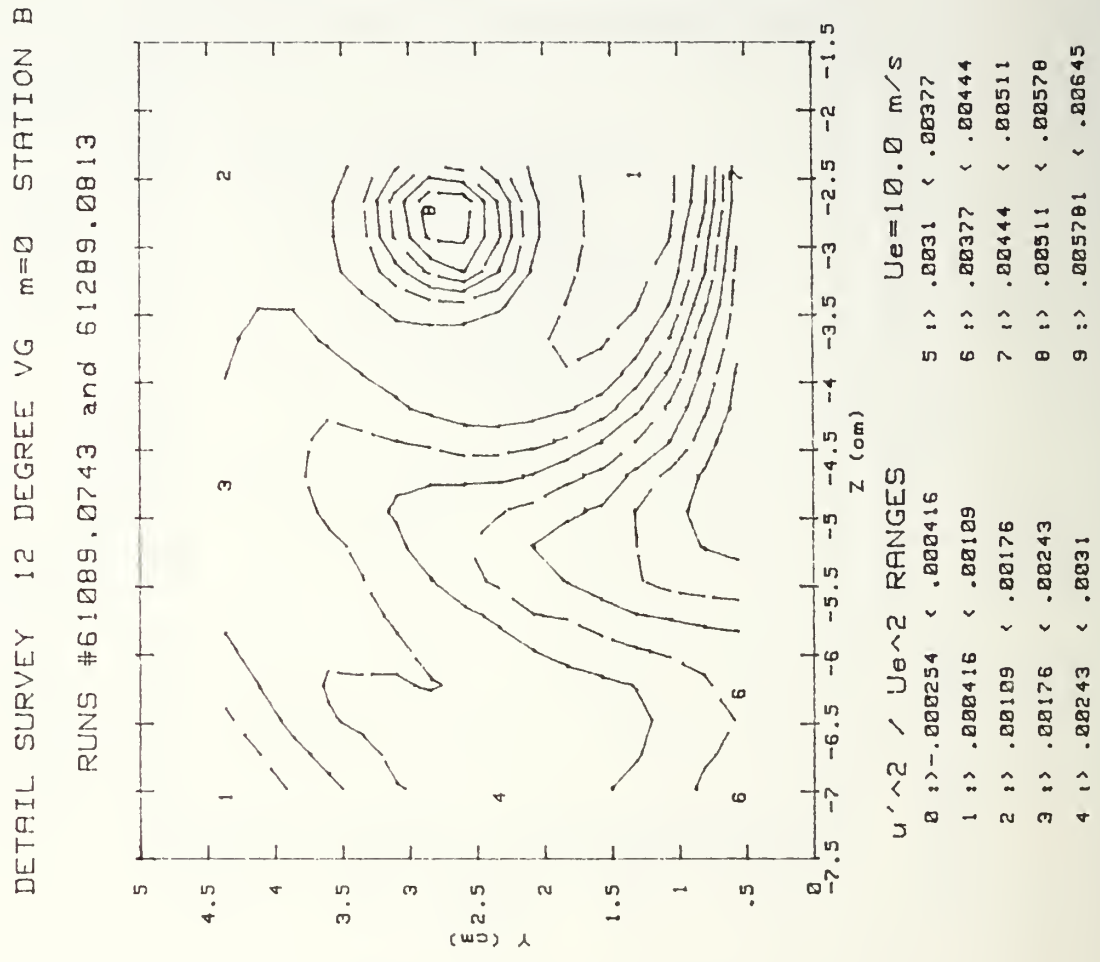

Figure 105. $\overline{u'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

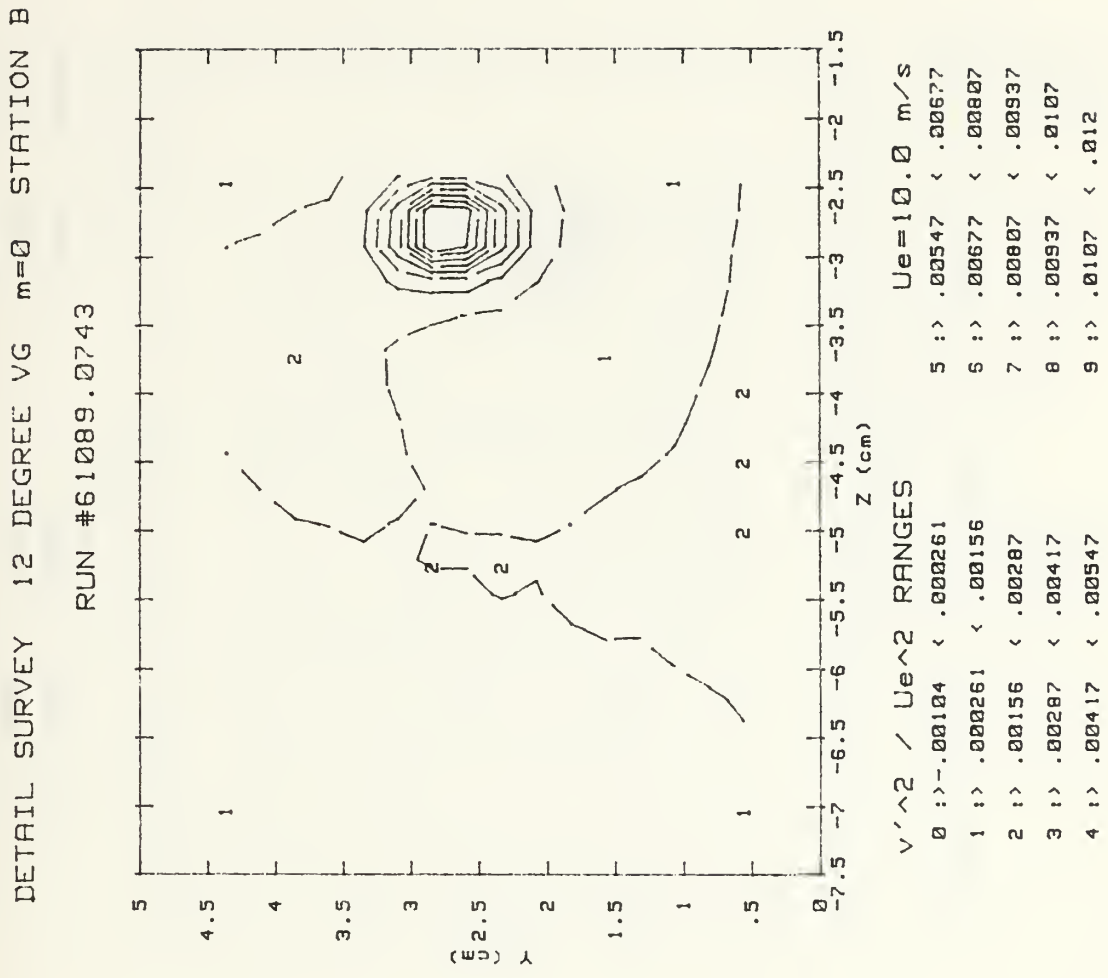

Figure 106. $\overline{v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

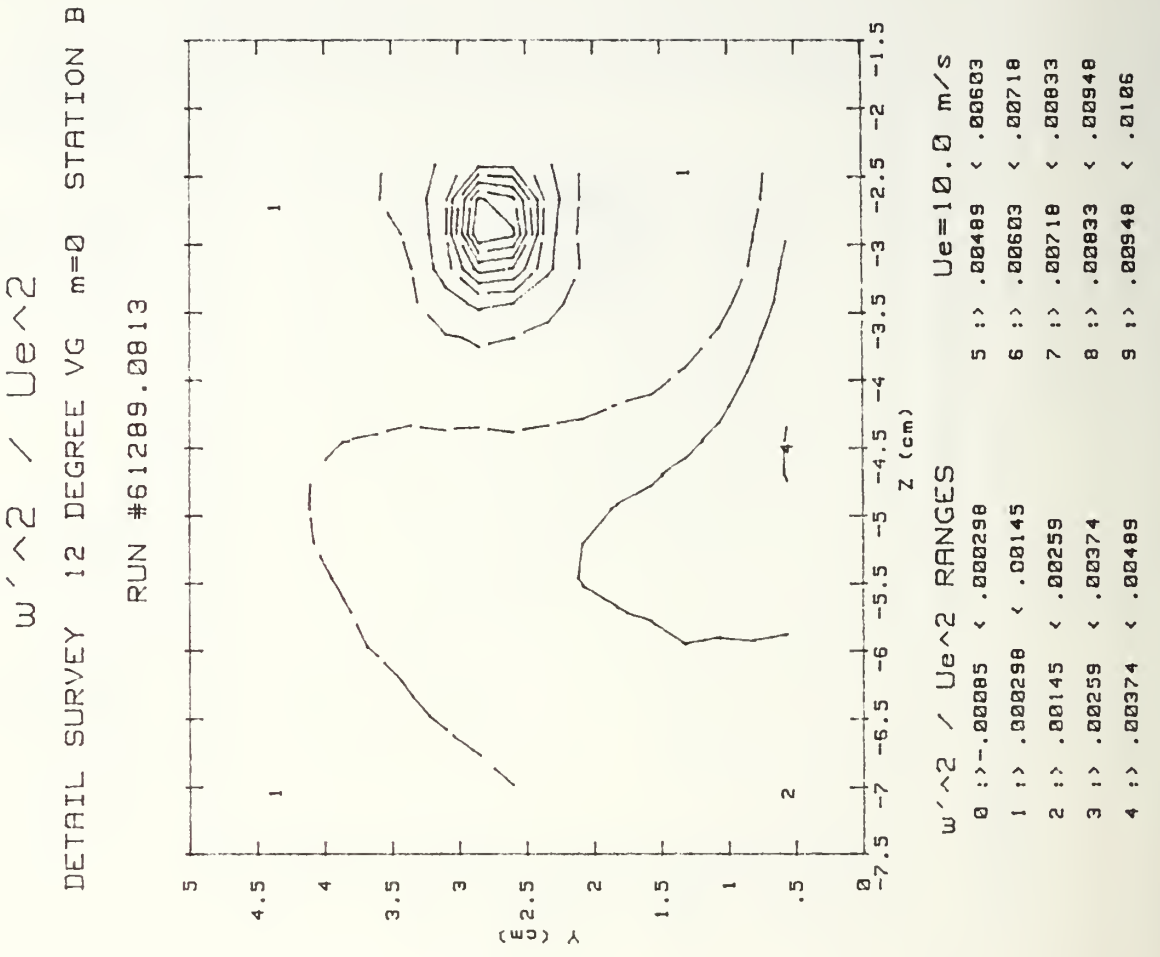

Figure 107. $\overline{w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

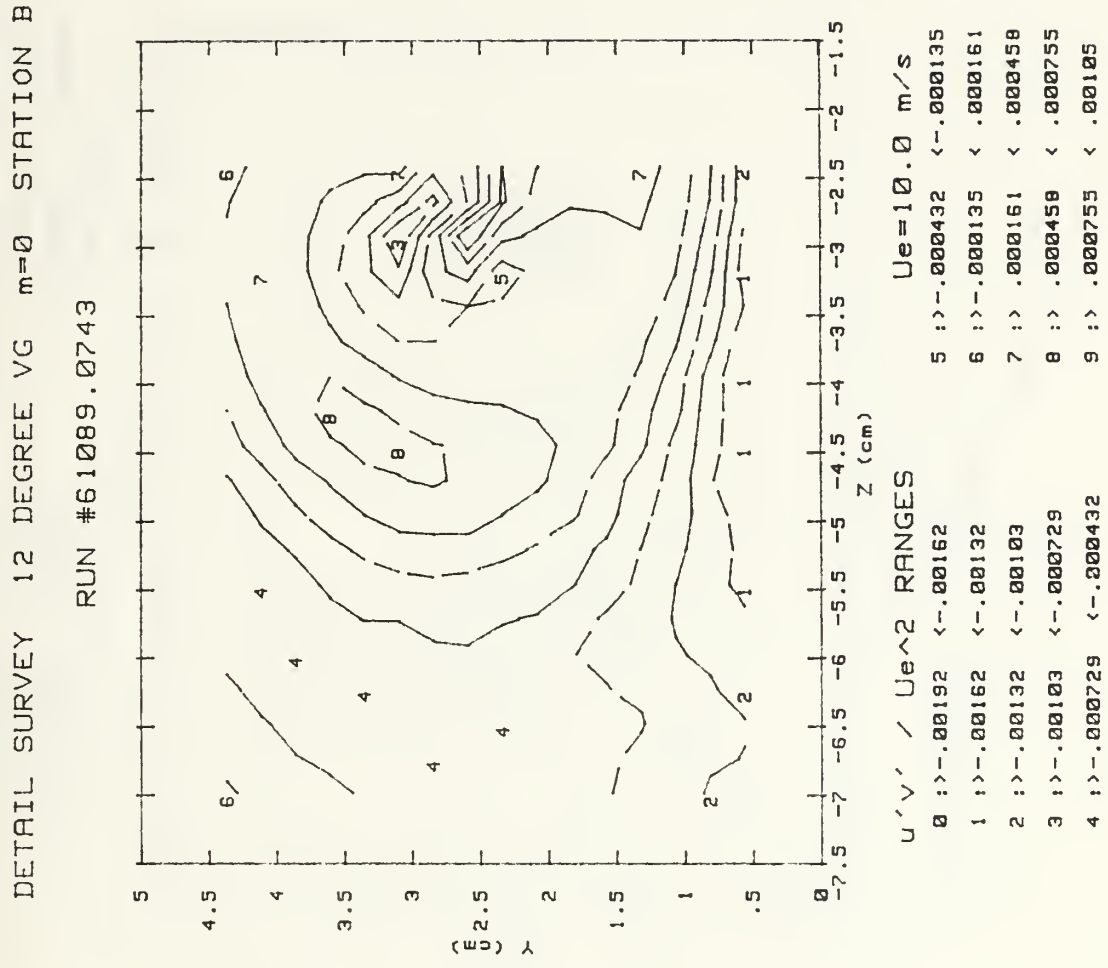

Figure 108. $\overline{u'v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

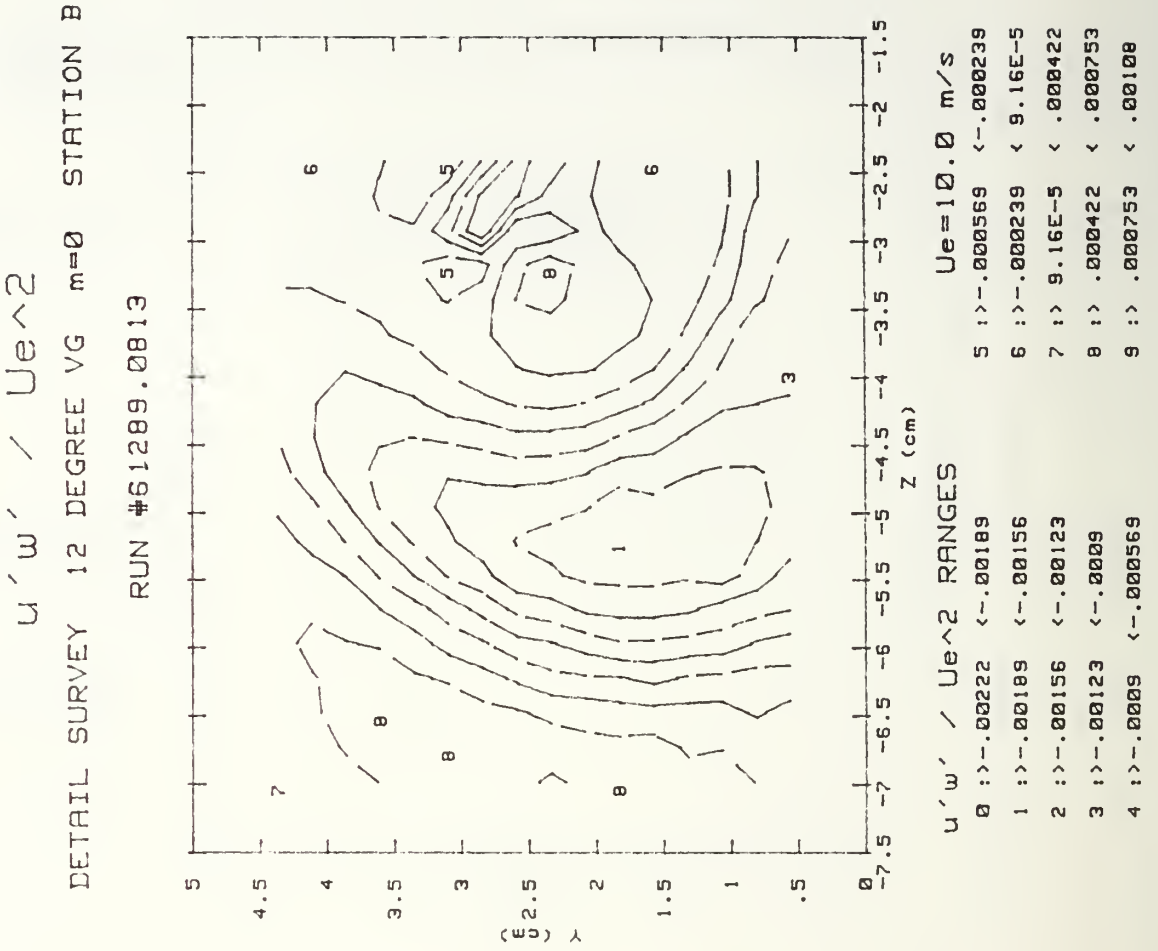

Figure 109. $\overline{u'w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

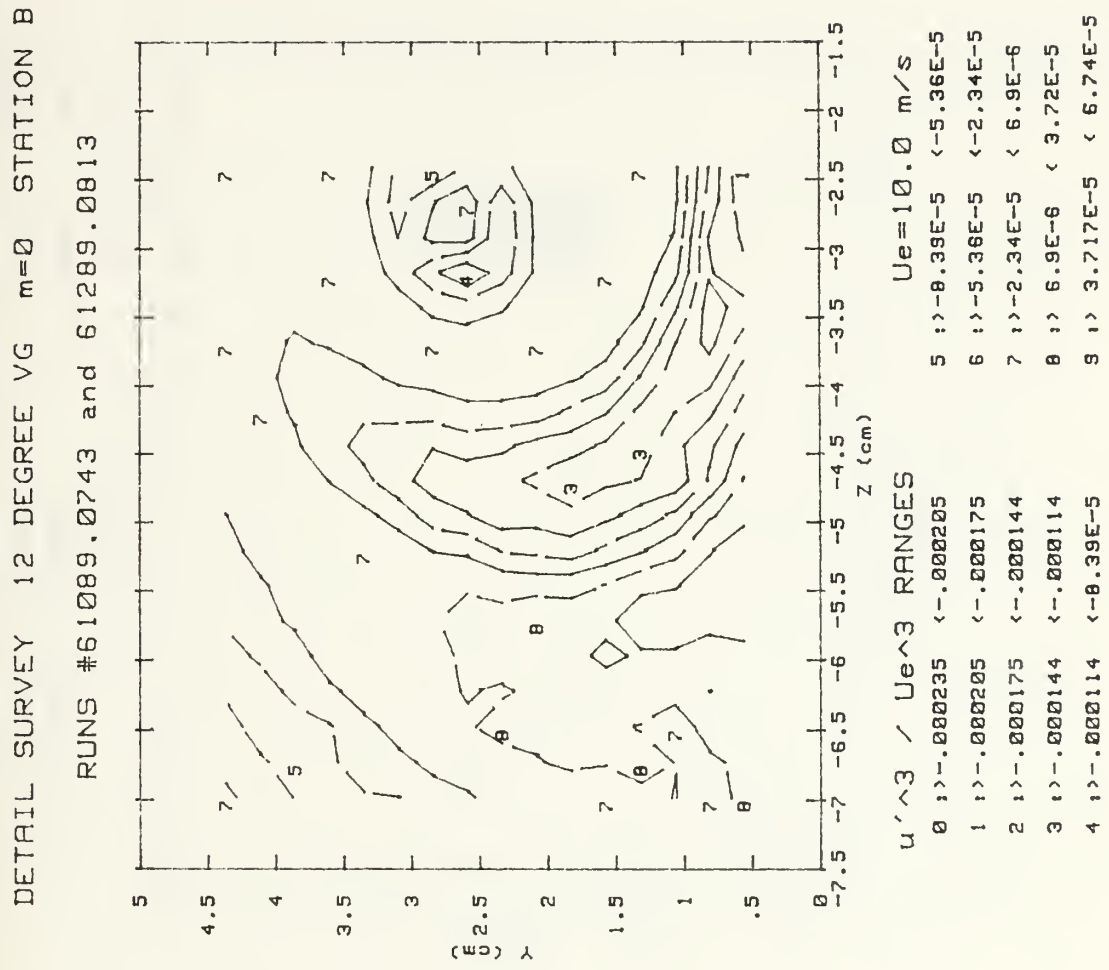

Figure 110. $\overline{u'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

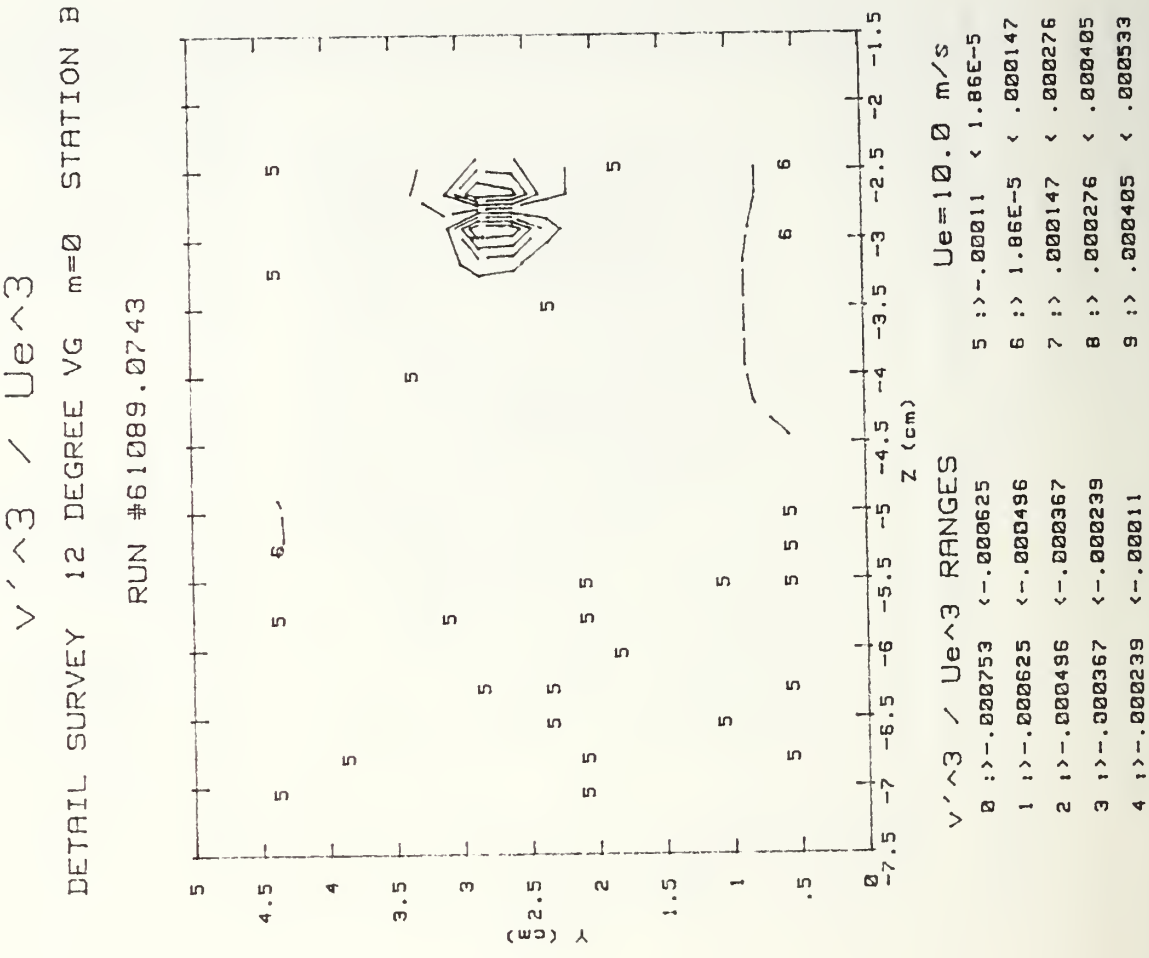

Figure 111. $\overline{v'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

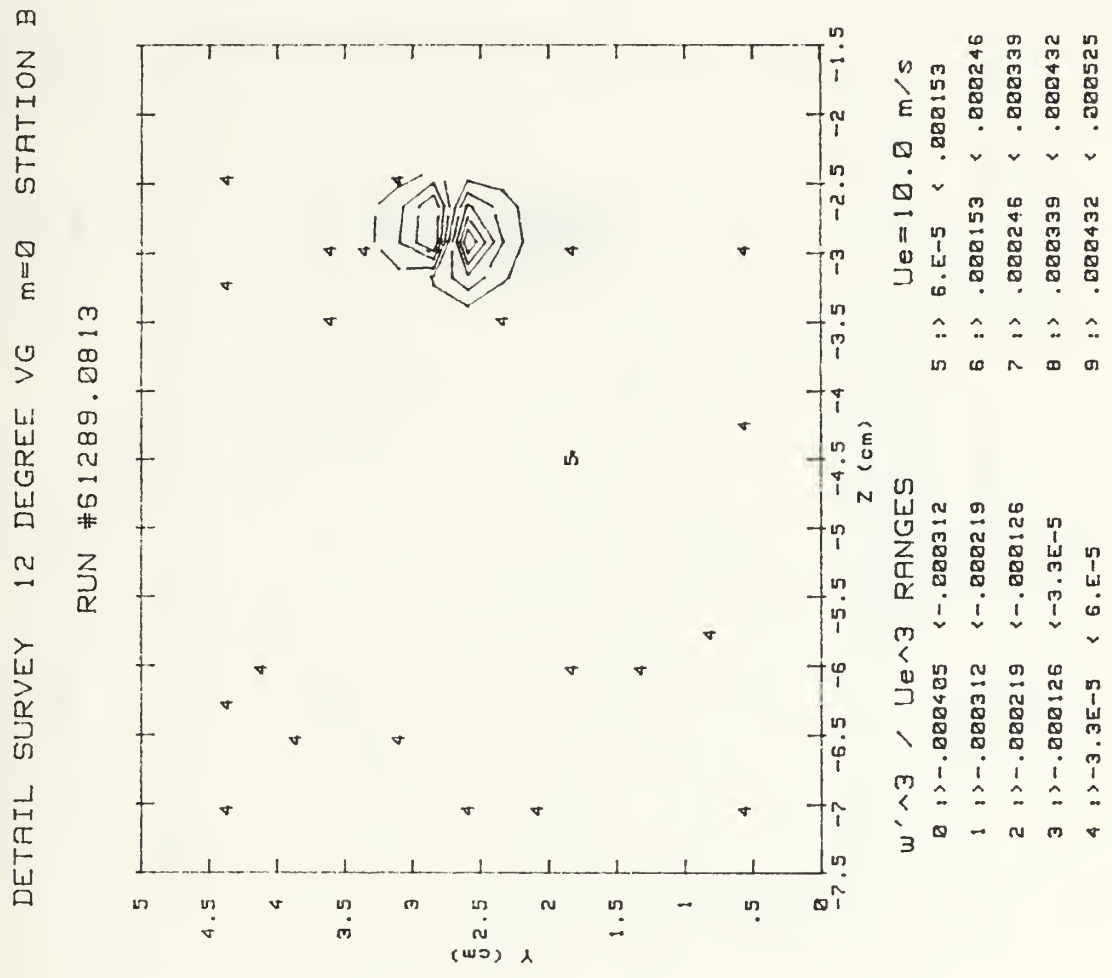

Figure 112. $\overline{w'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

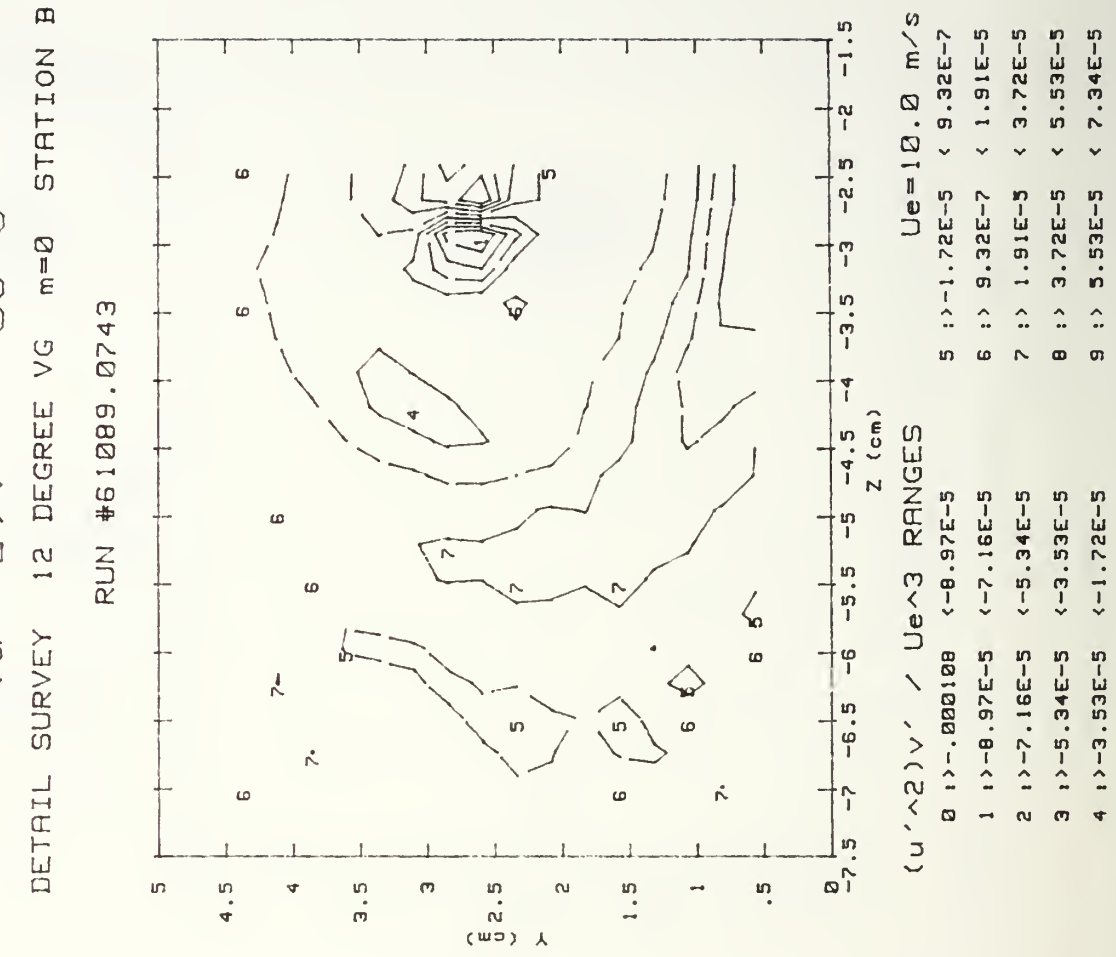

Figure 113. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

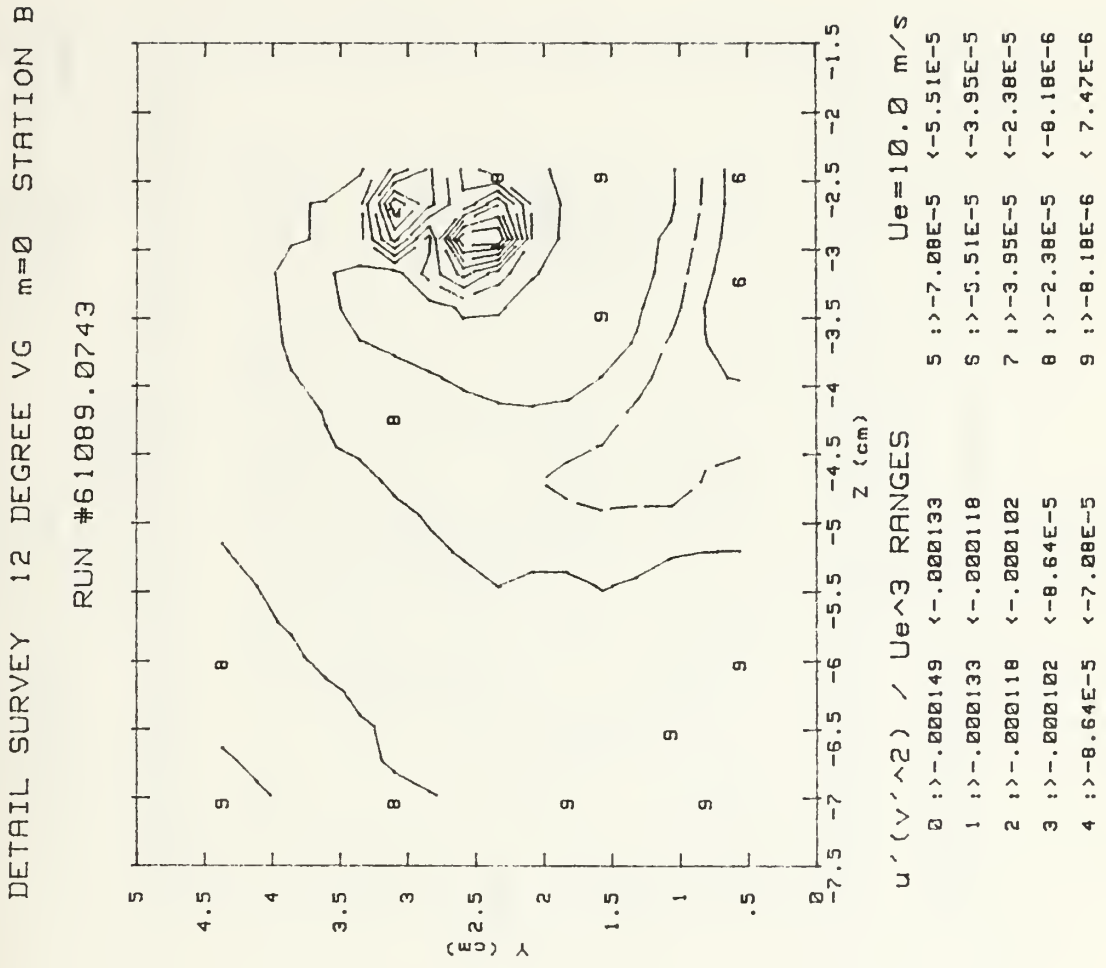

Figure 114. $\overline{u'v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

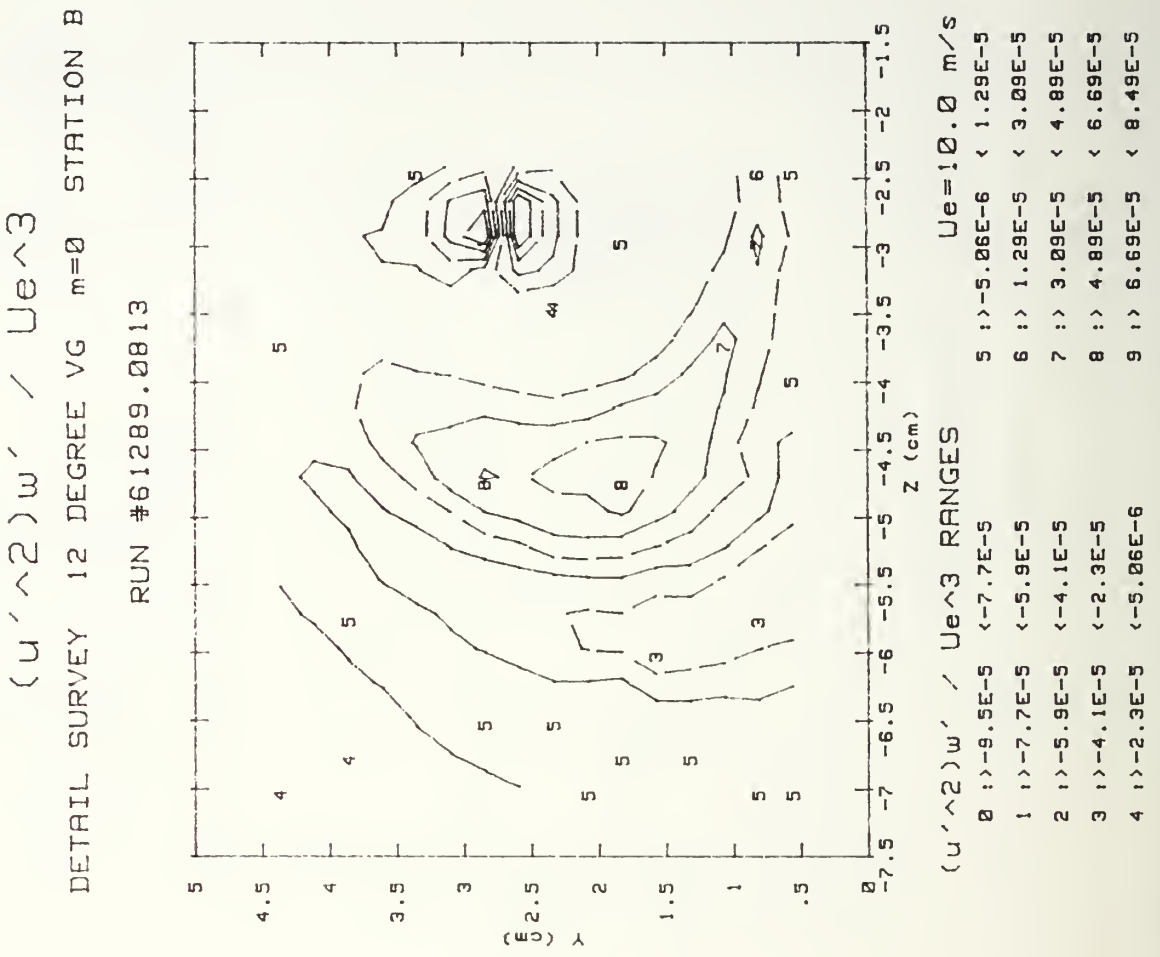

Figure 115. $\overline{u'^2w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

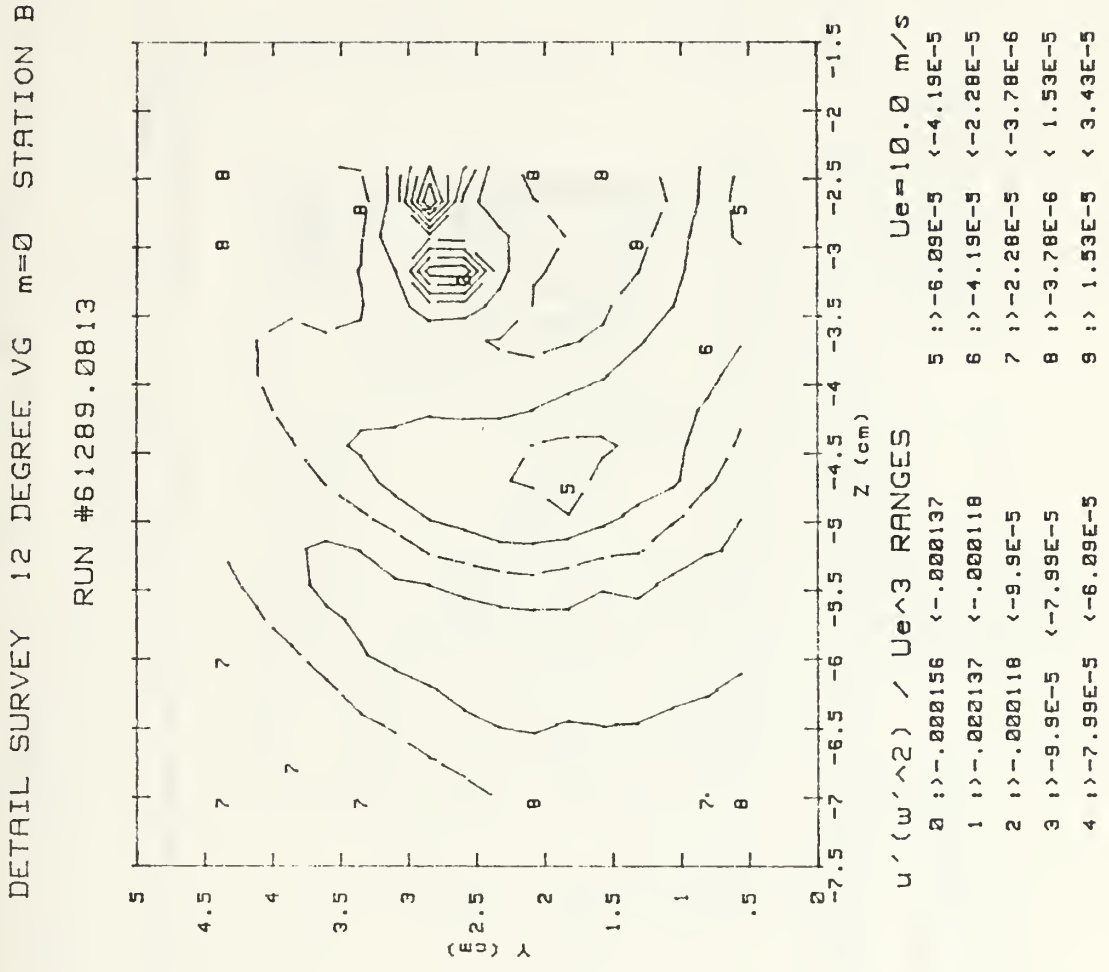

Figure 116. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

Figure 117. Streamwise Vorticity (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 0, Δ = 0.10)

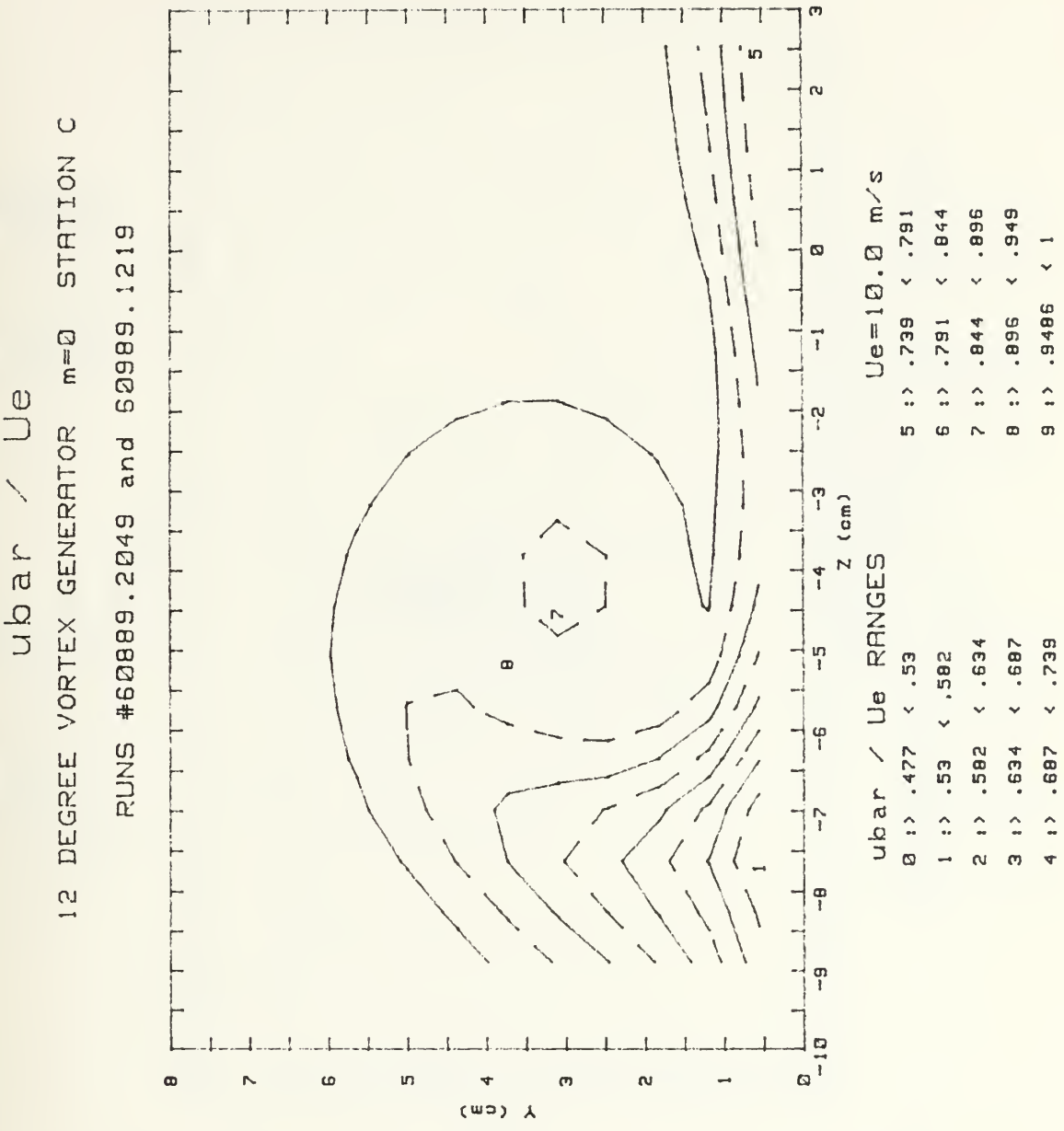

Figure 118. $\bar{u}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ= 0.25)

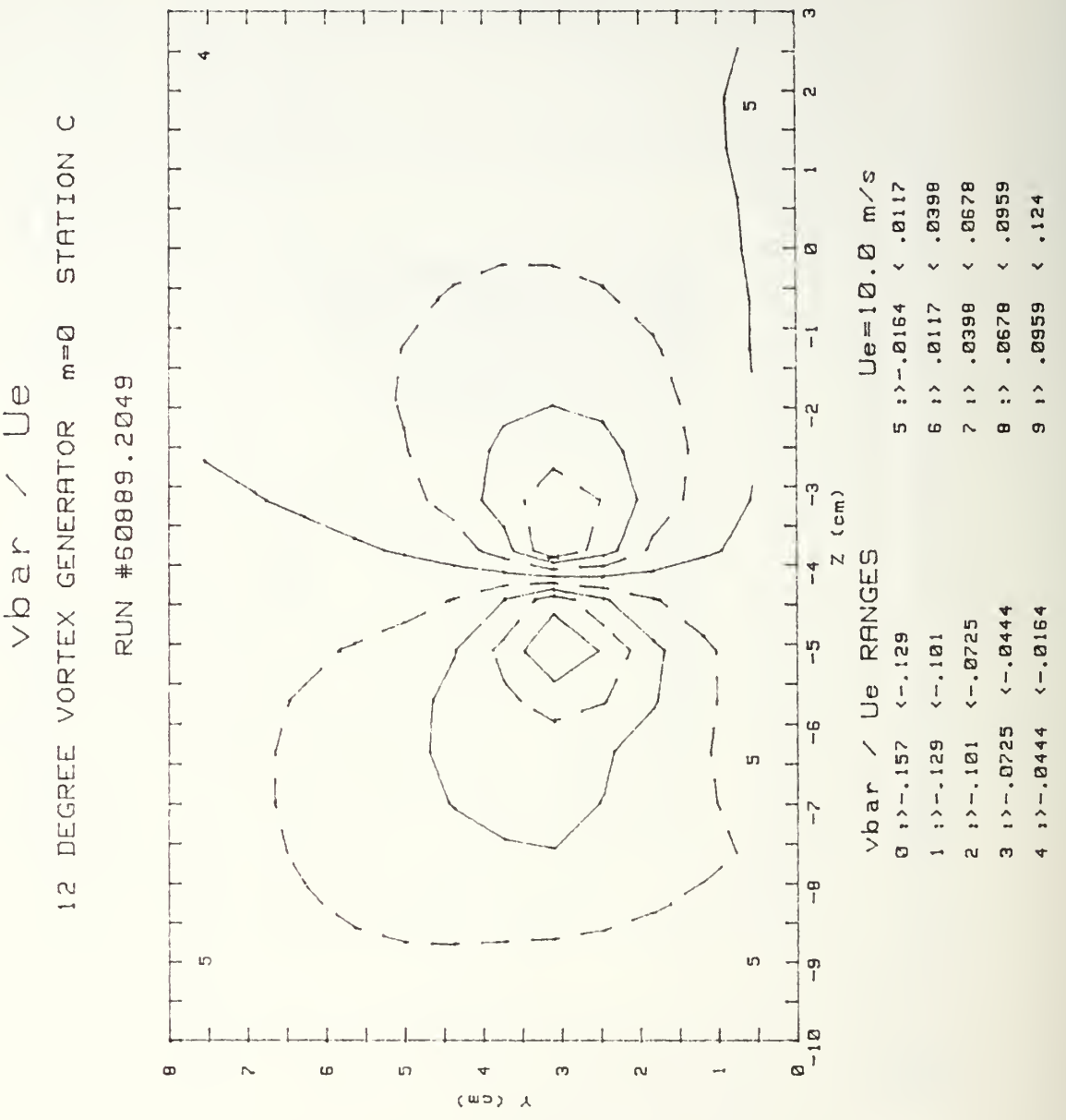

Figure 119. $\overline{v}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

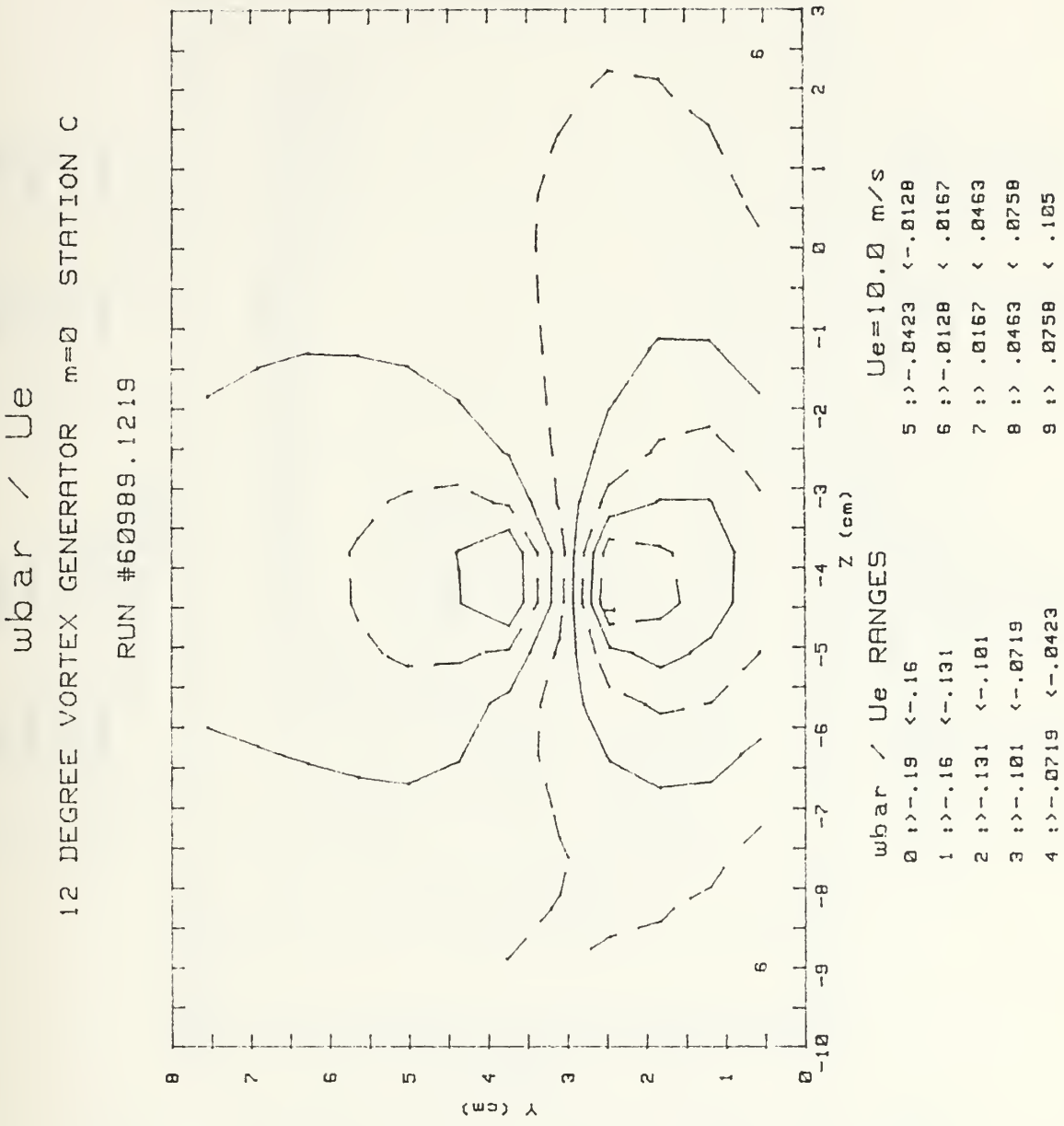

Figure 120. $\overline{w}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

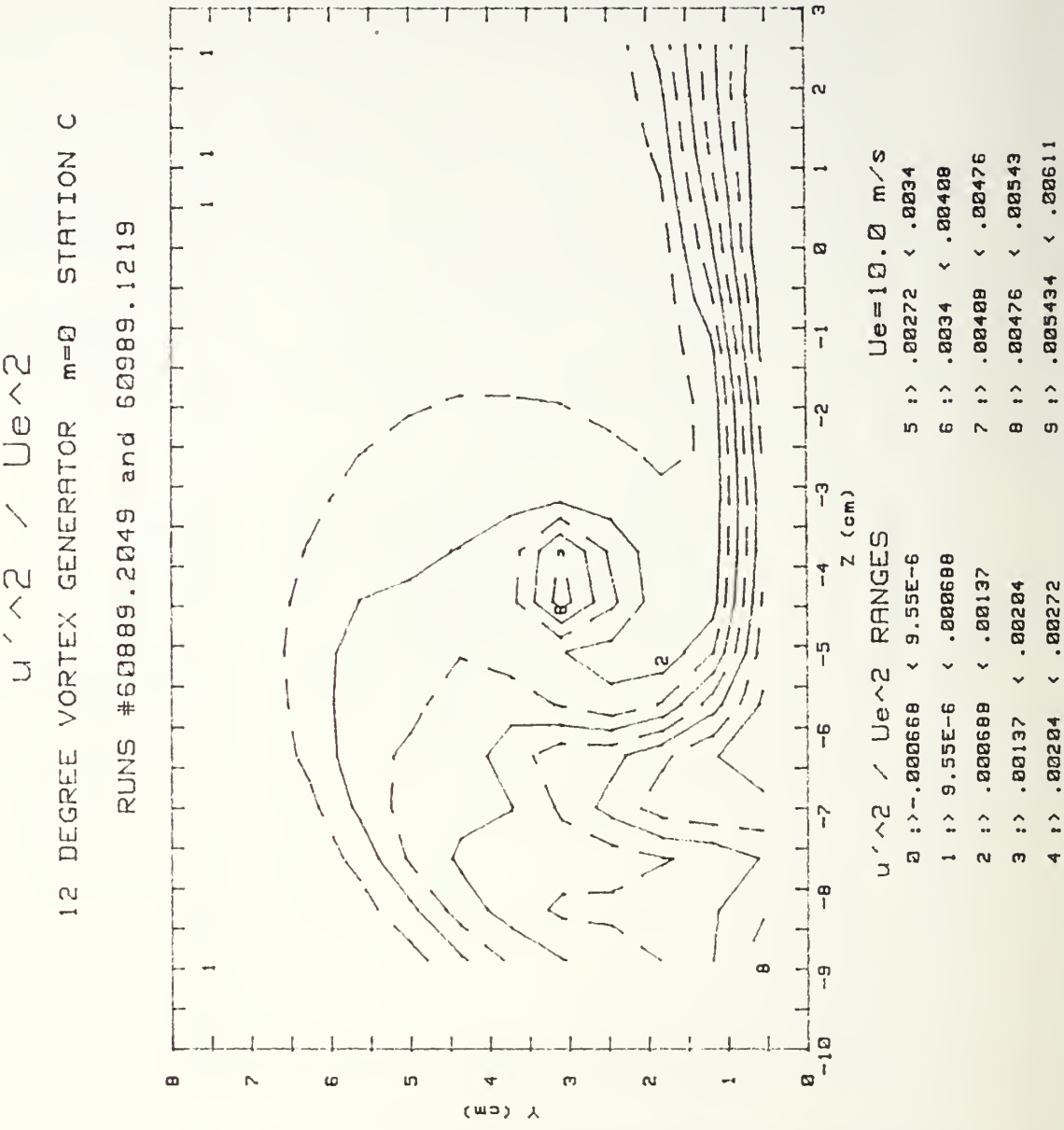

Figure 121. $\overline{u'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

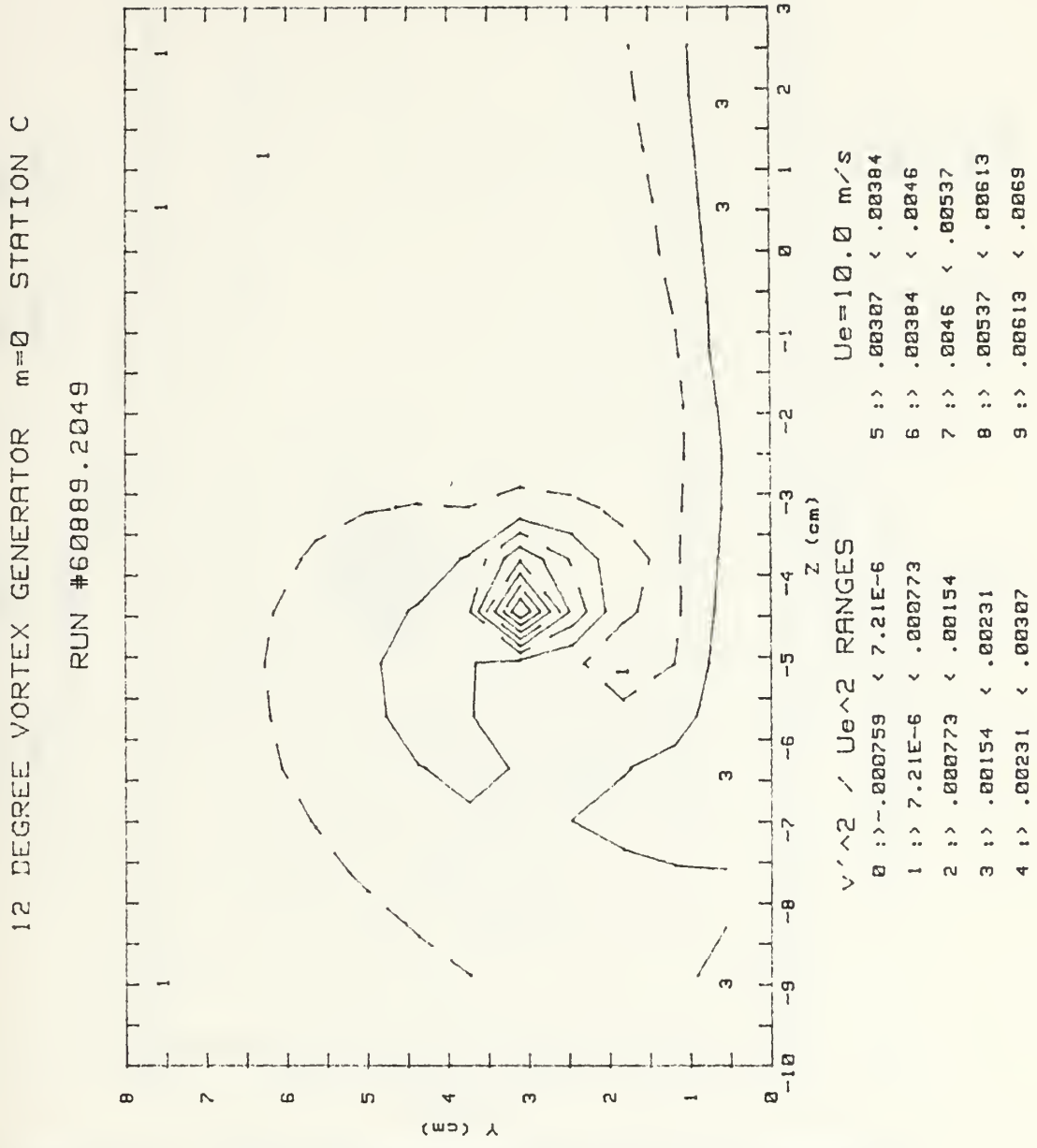

Figure 122. $\overline{v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

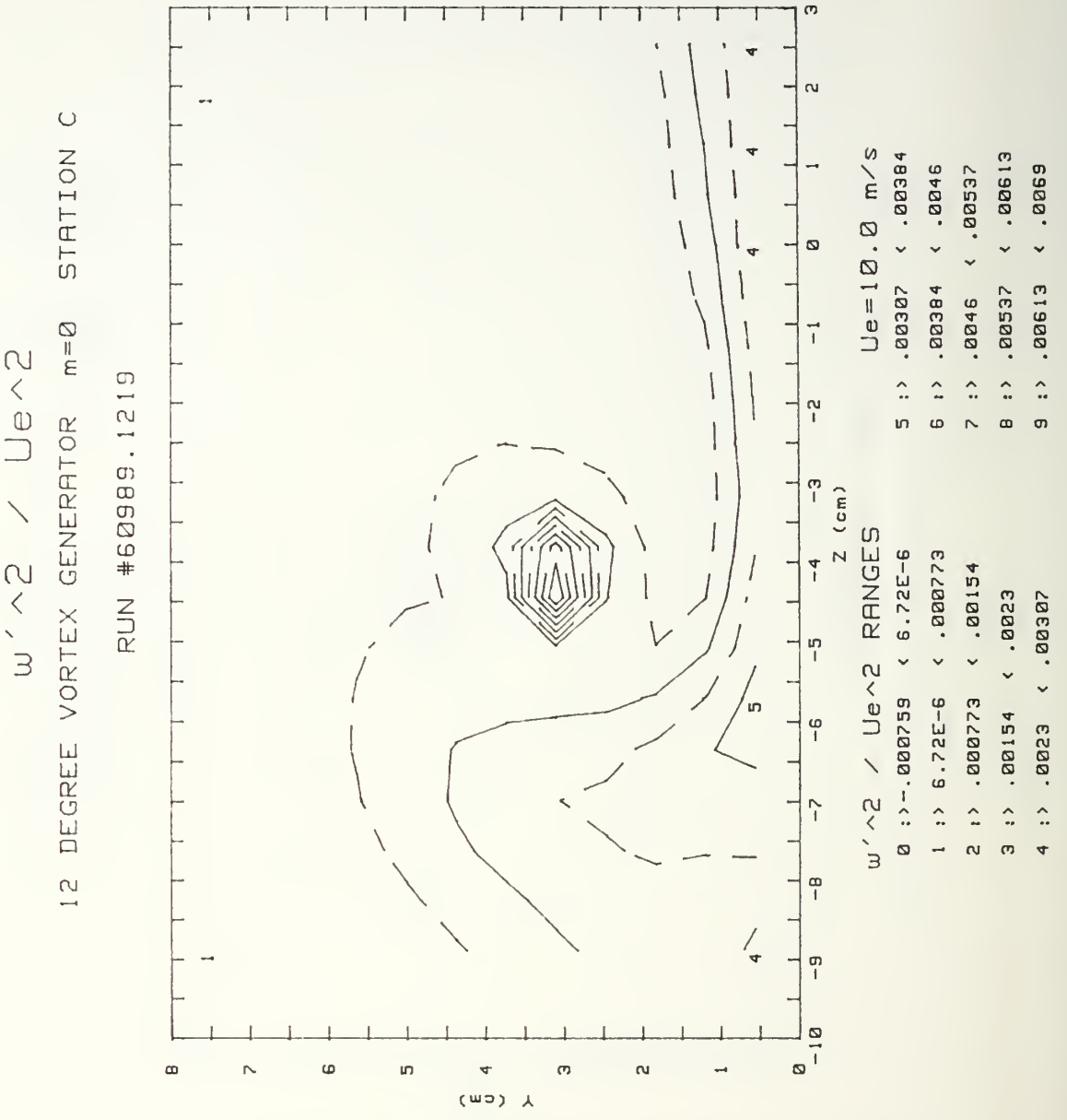

Figure 123. $\overline{w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

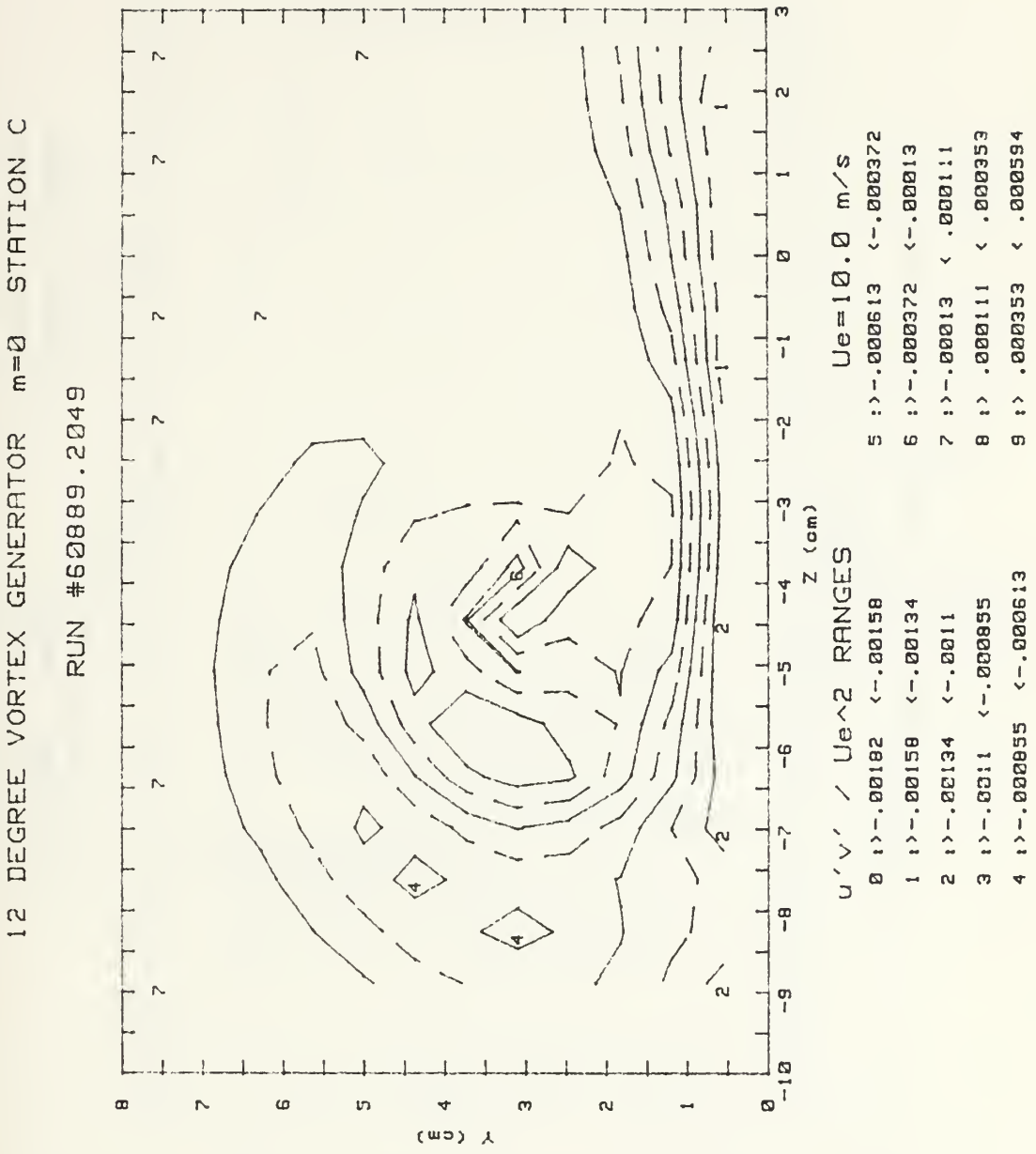

Figure 124. $\overline{u'v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

Figure 125. $\overline{u'w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

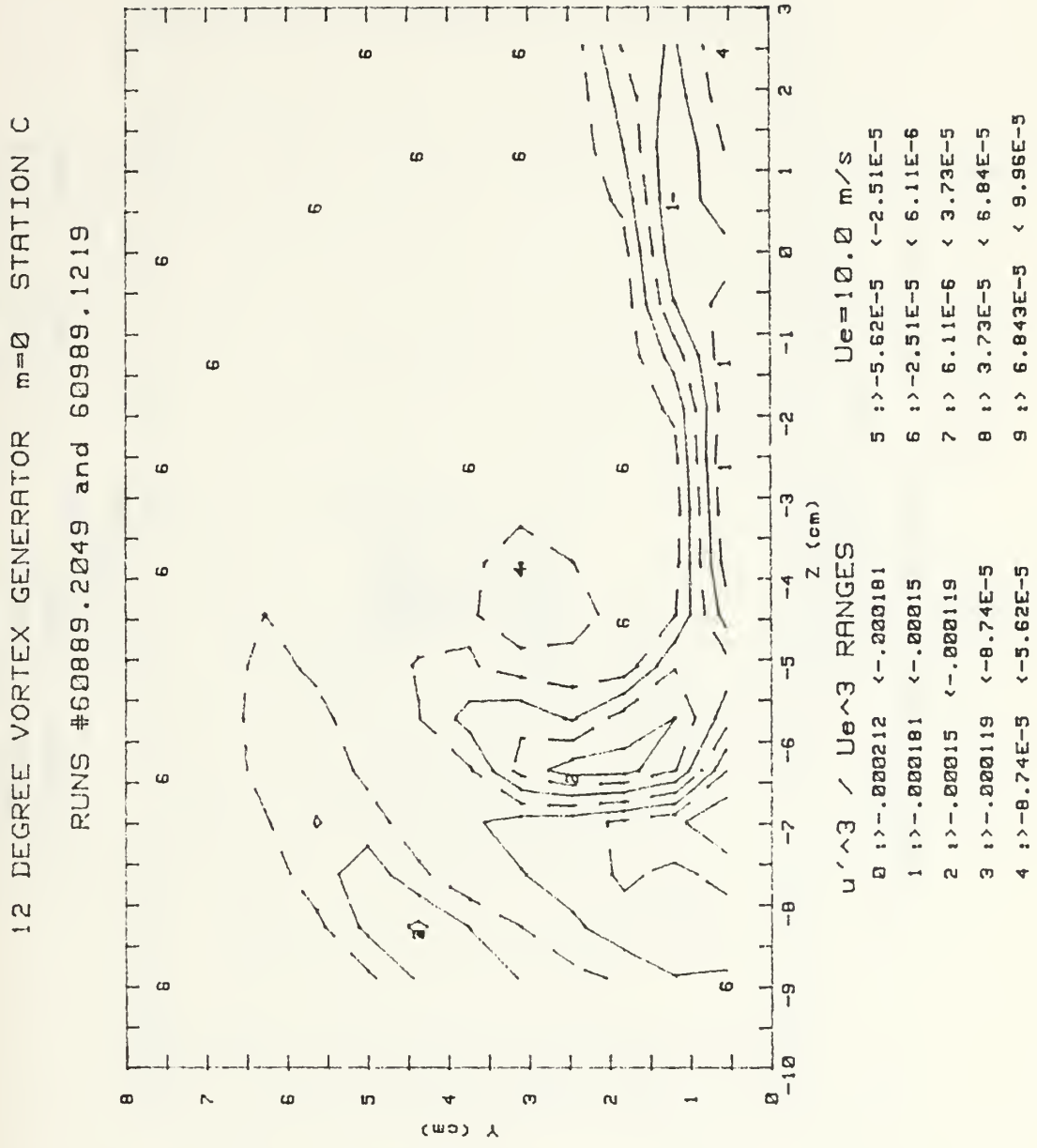

Figure 126. $\overline{u'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

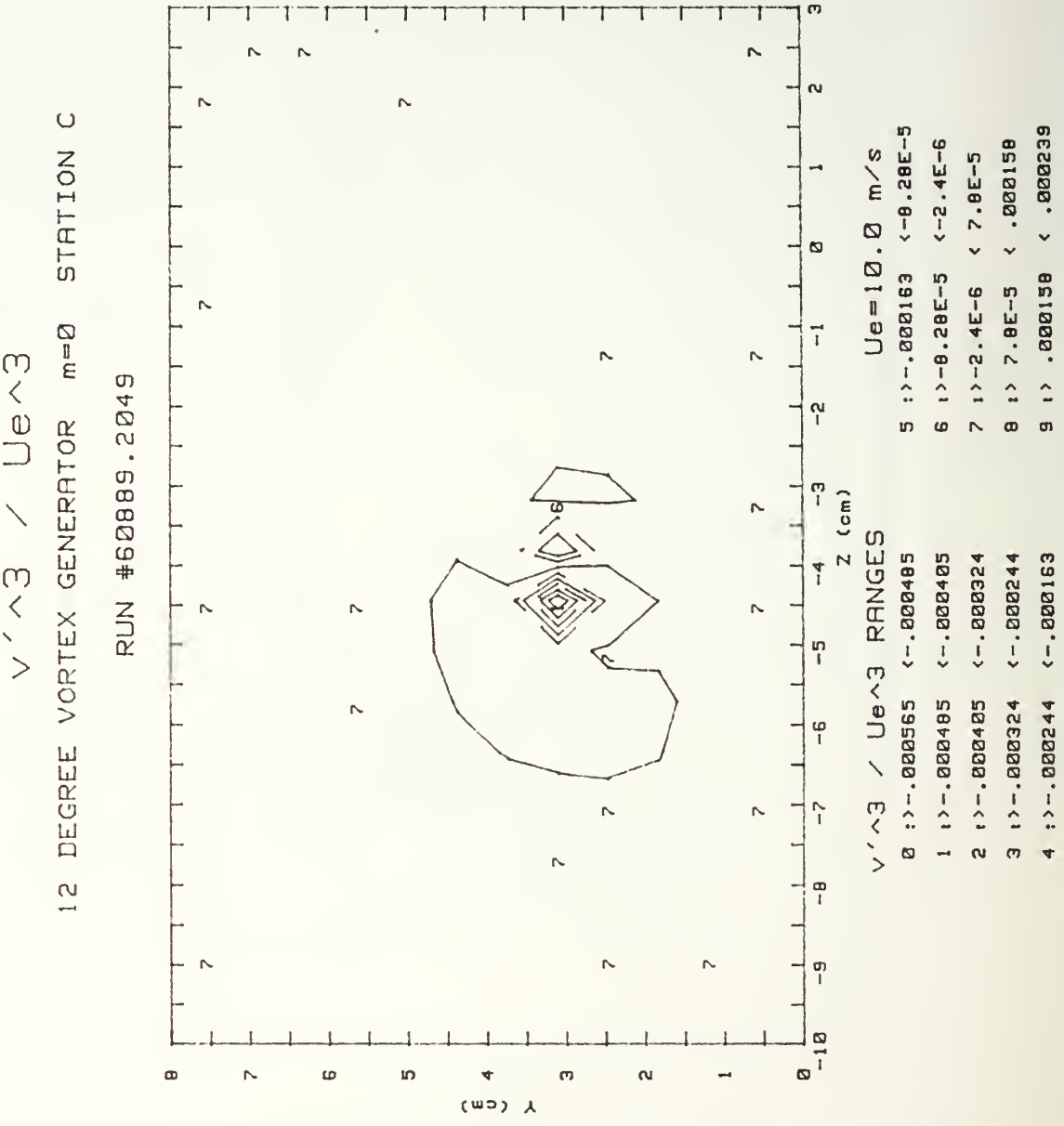

Figure 127. $\overline{v'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

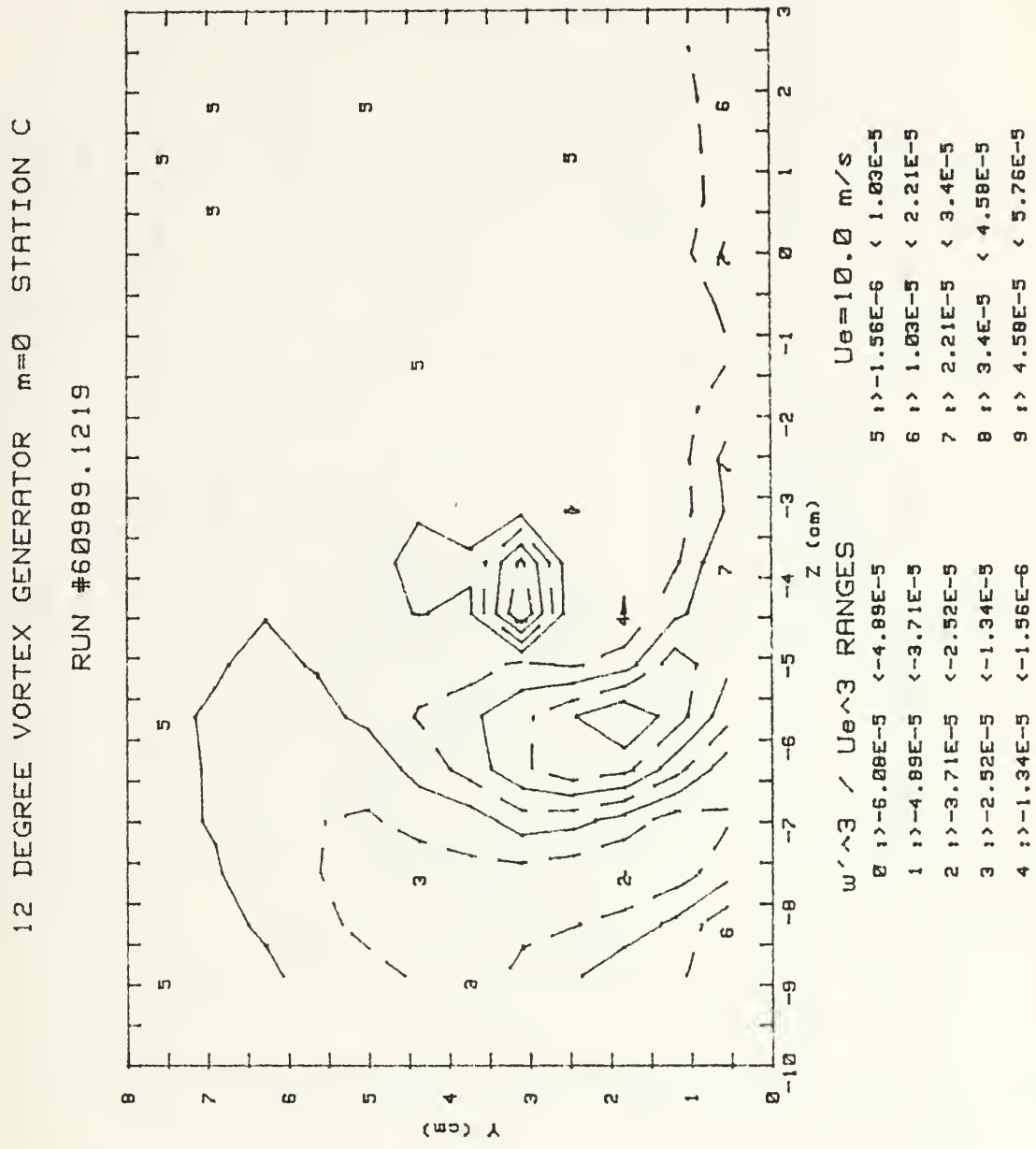

Figure 128. $\overline{w'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

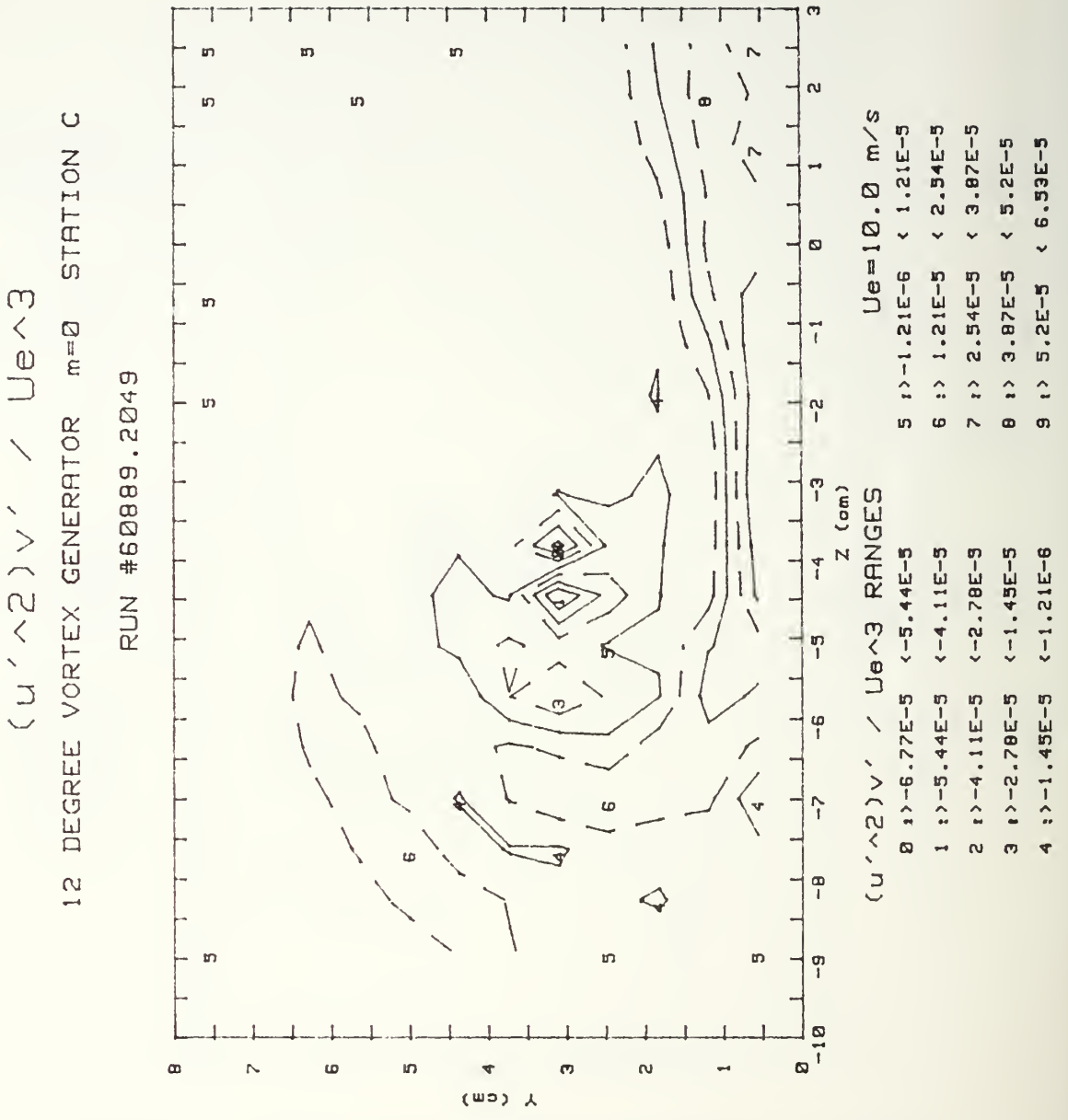

Figure 129. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

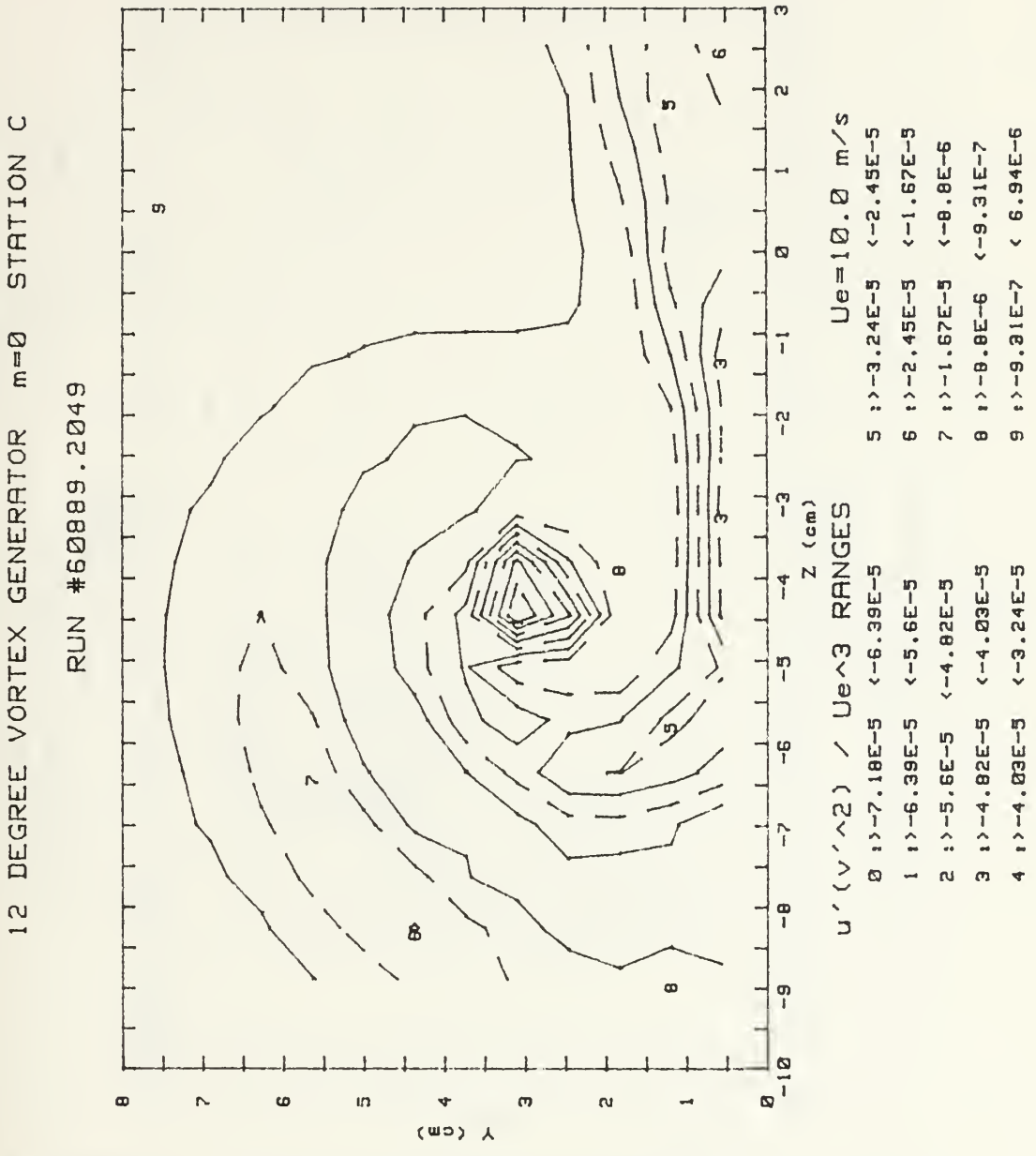

Figure 130. $\overline{u'v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

Figure 131. $\overline{u'^2w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ= 0.25)

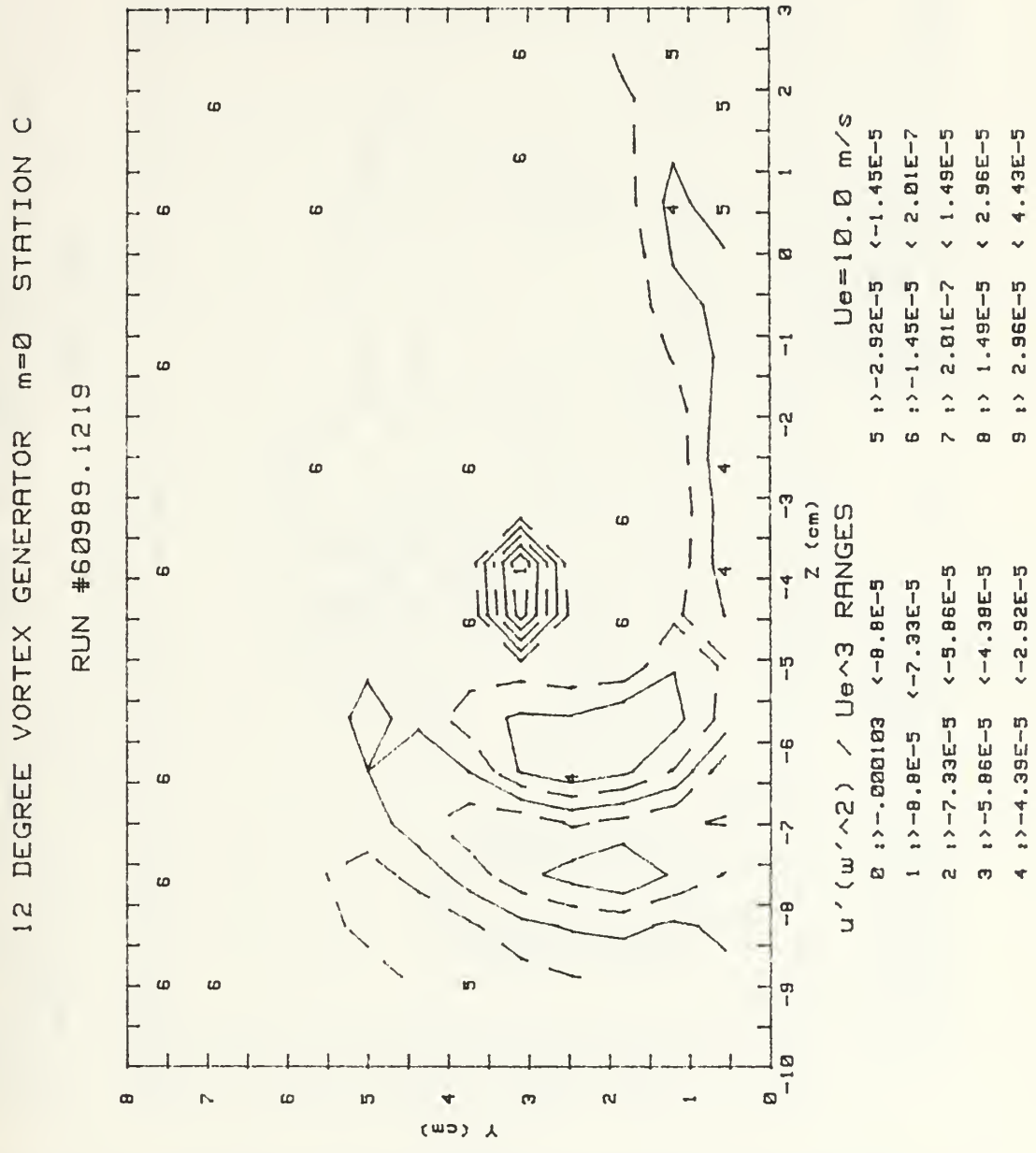

Figure 132. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

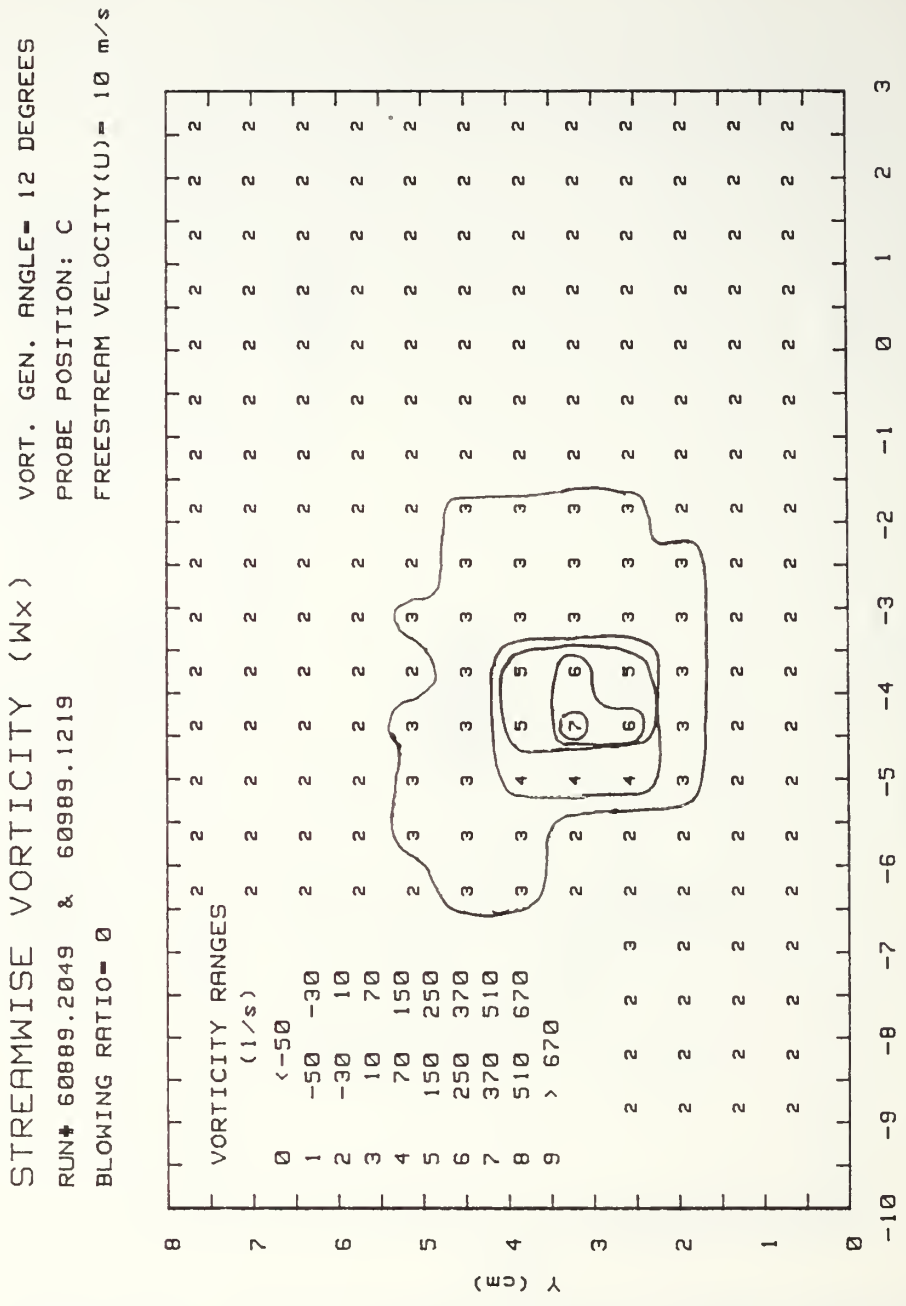

Figure 133. Streamwise Vorticity (Boundary Layer w/vortex, Downwash @ Centerline, Station C, m = 0, Δ = 0.25)

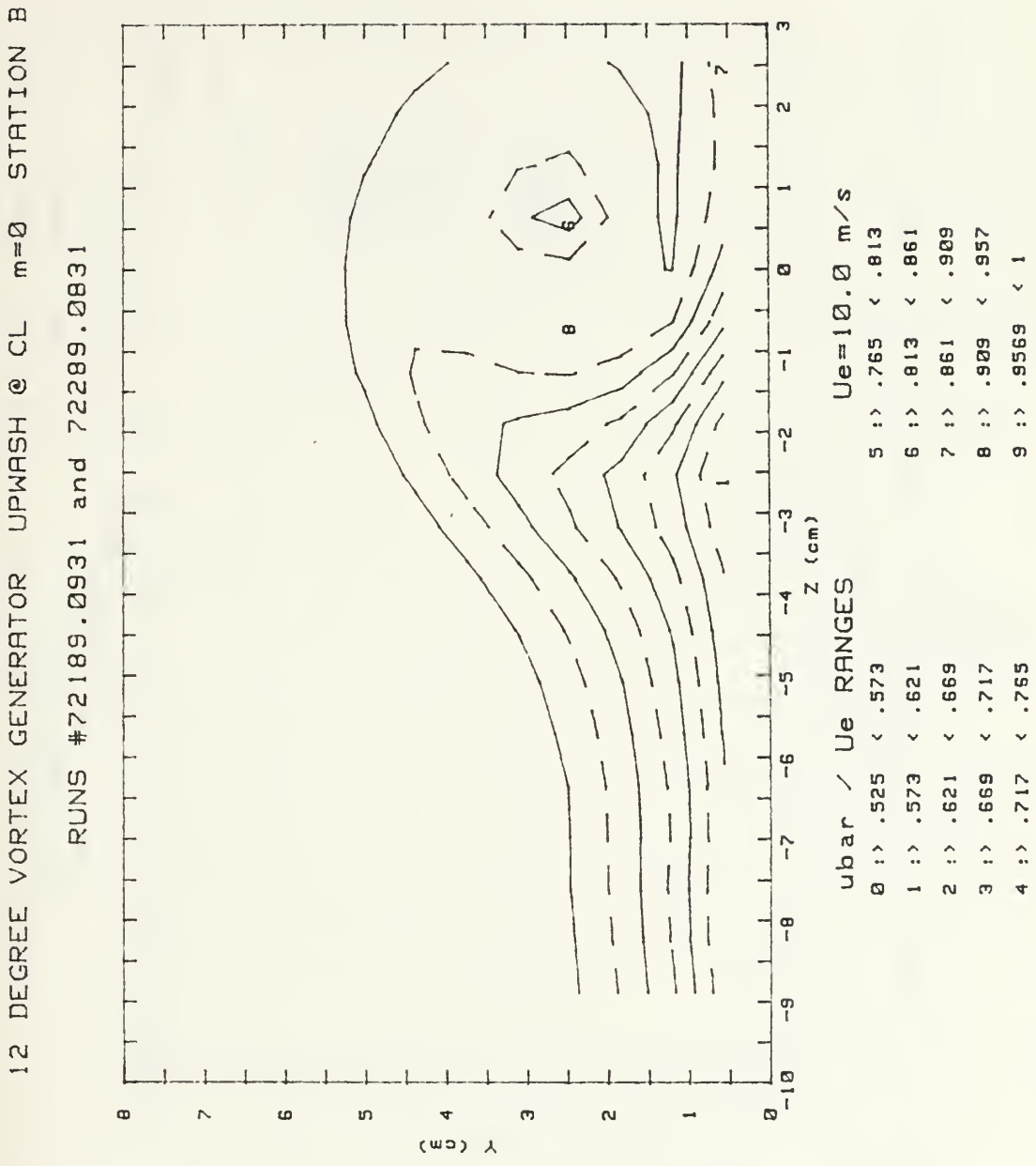

Figure 134. $\overline{u}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ= 0.25)

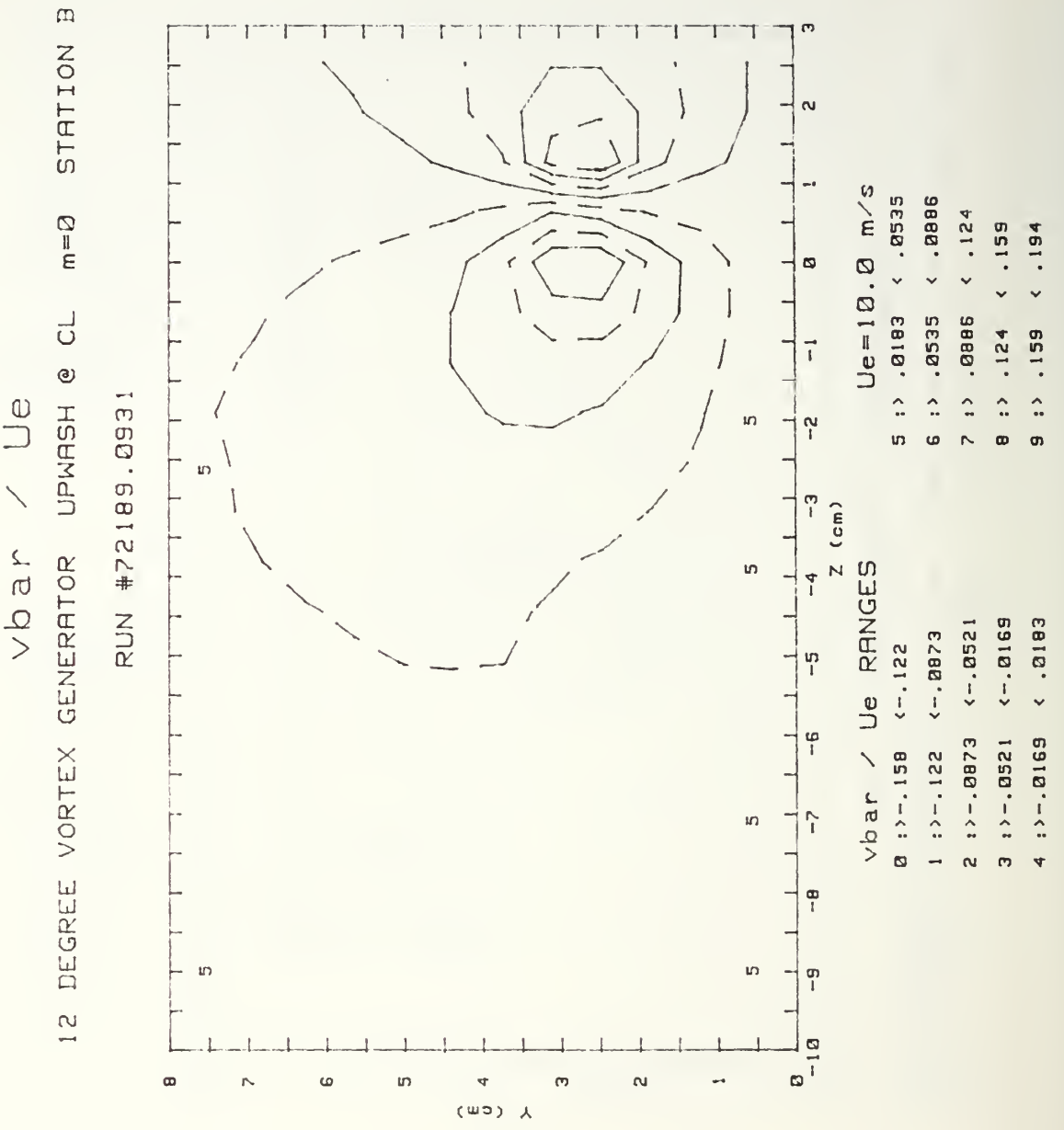

Figure 135. $\bar{v}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

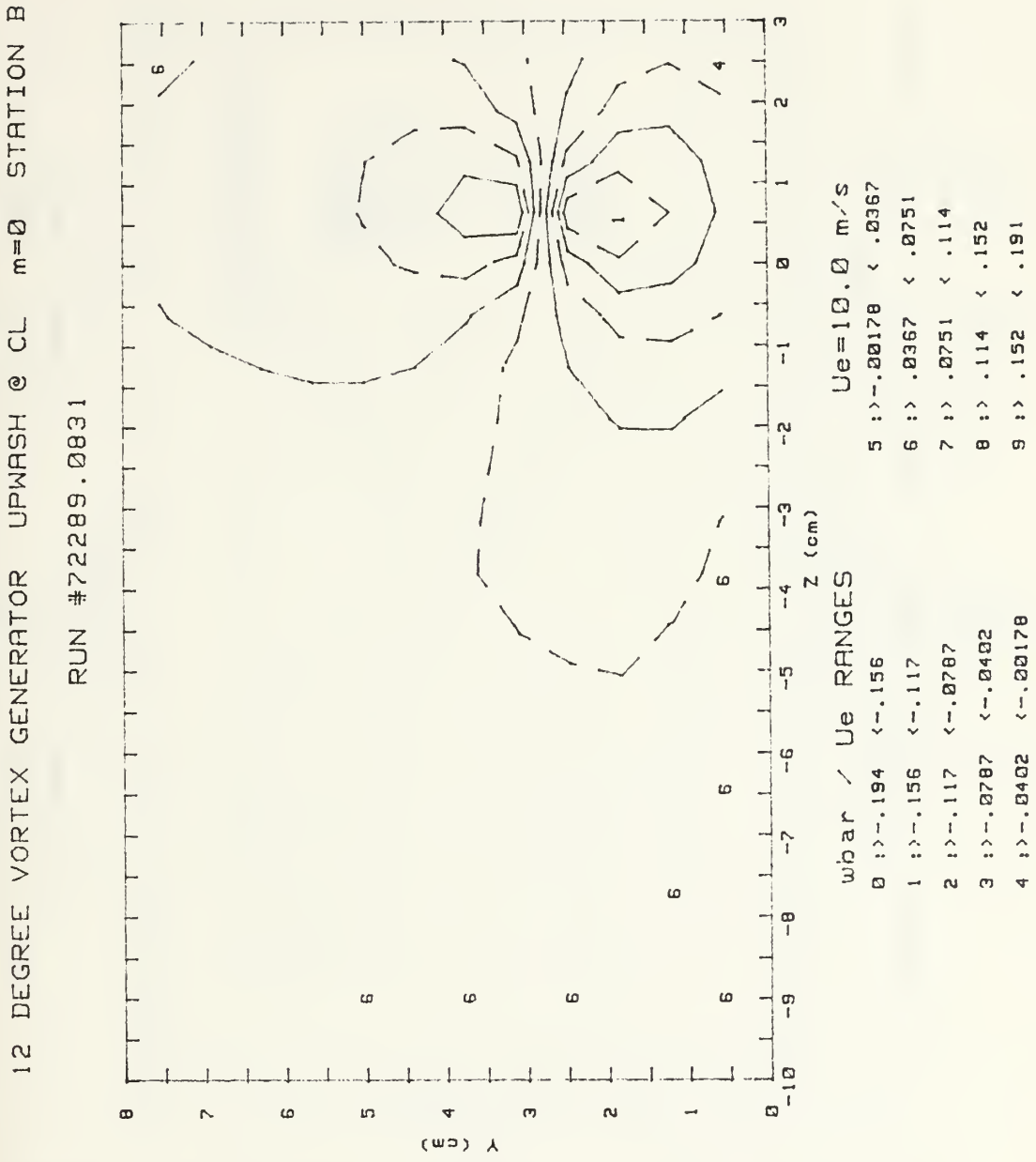

Figure 136. $\overline{w}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

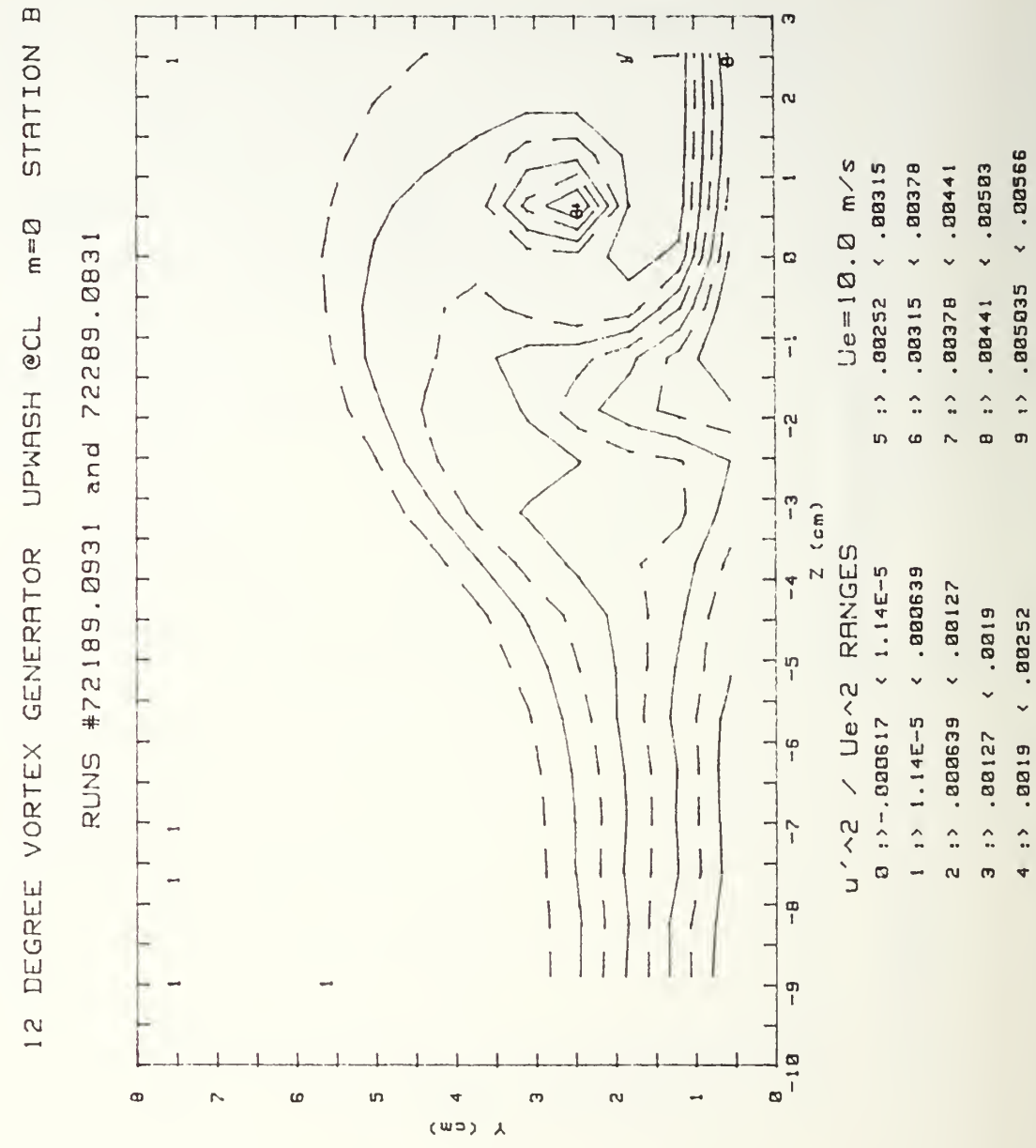

Figure 137. $\overline{u'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

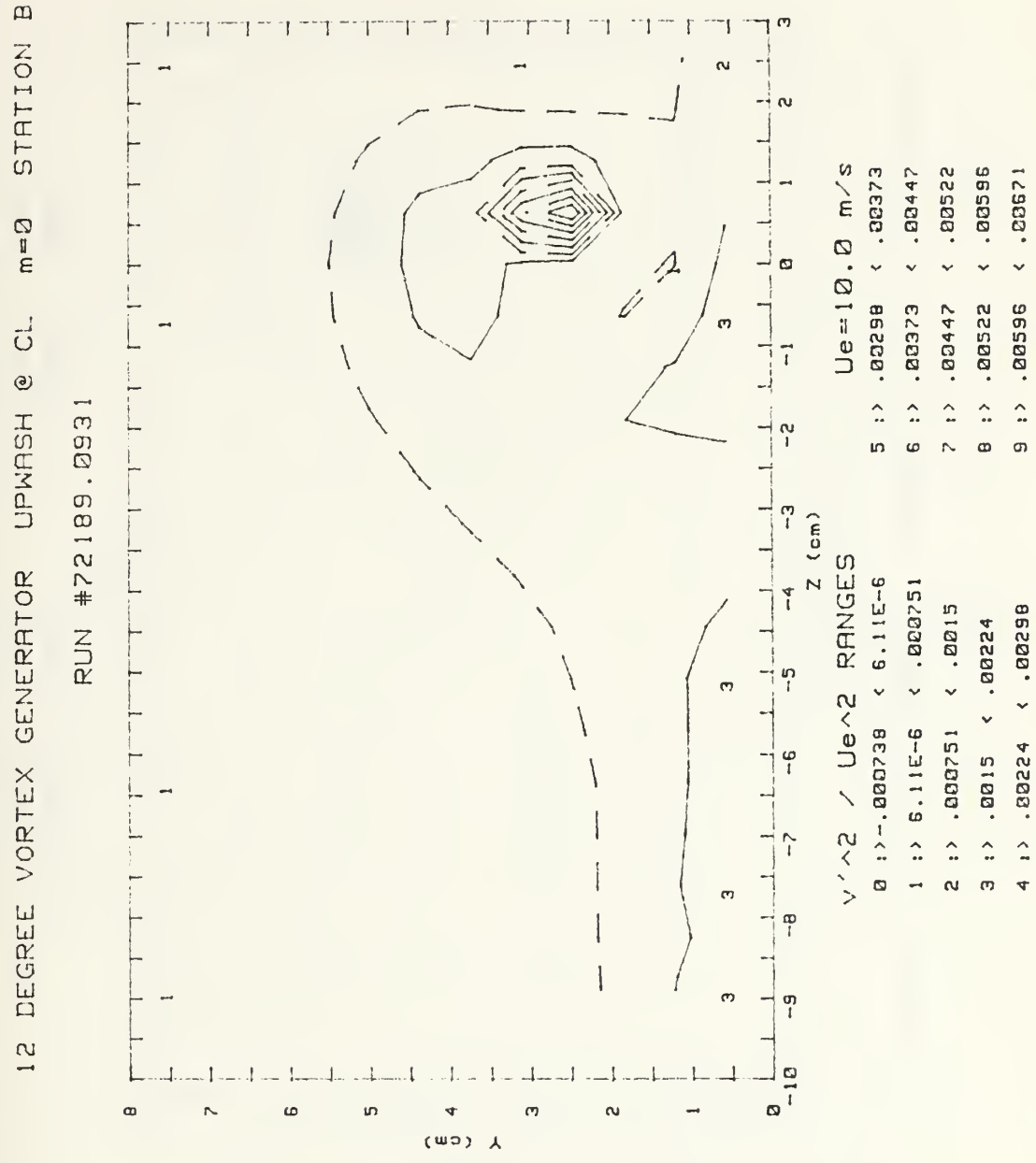

Figure 138. $\overline{v'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

Figure 139. $\overline{w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

Figure 140. $\overline{u'v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

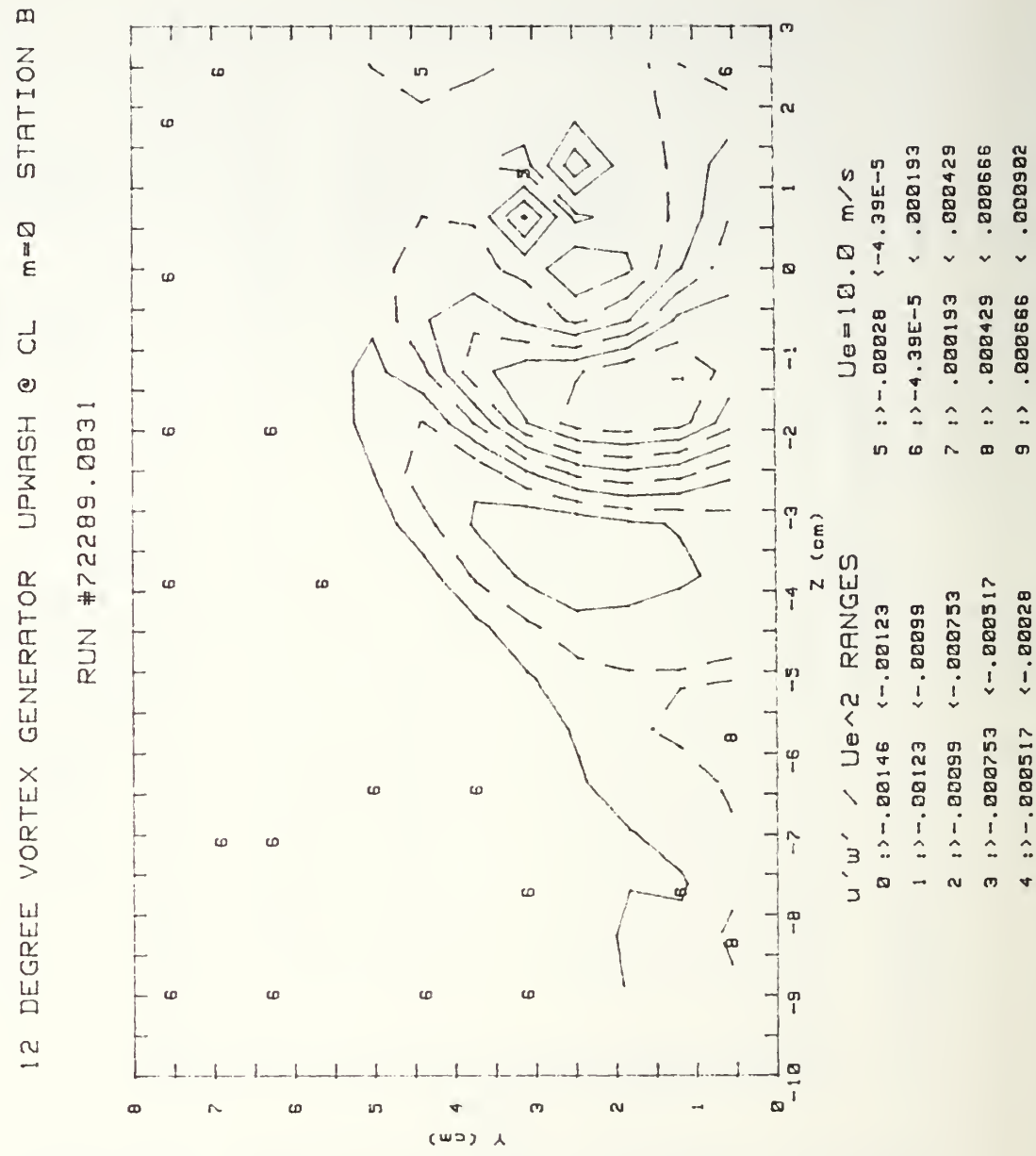

Figure 141. $\overline{u'w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

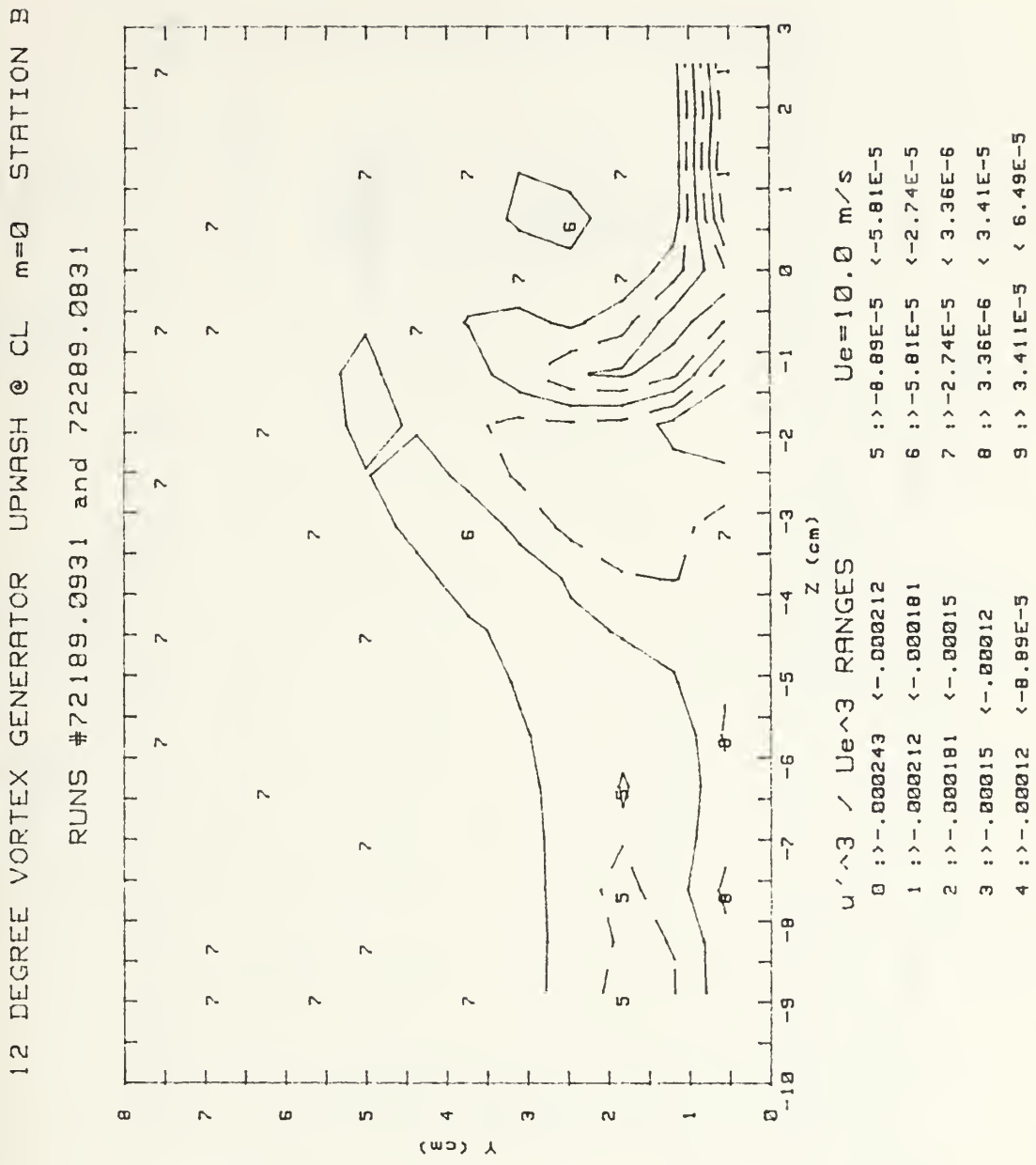

Figure 142. $\overline{u'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

Figure 143. $\overline{v'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

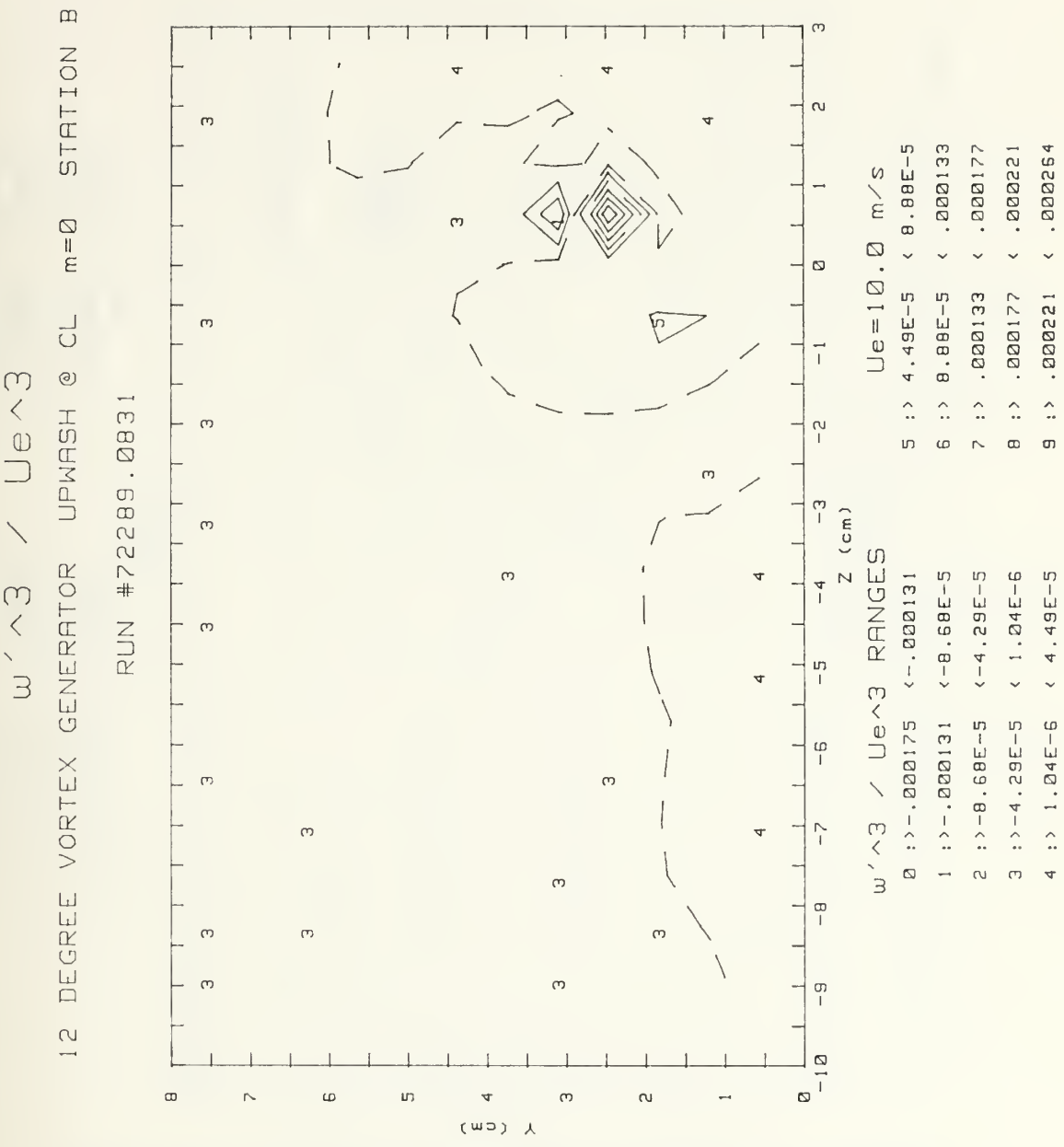

Figure 144. $\overline{w'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

Figure 145. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

Figure 146. $\overline{u'v'^2}$ (Boundary layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

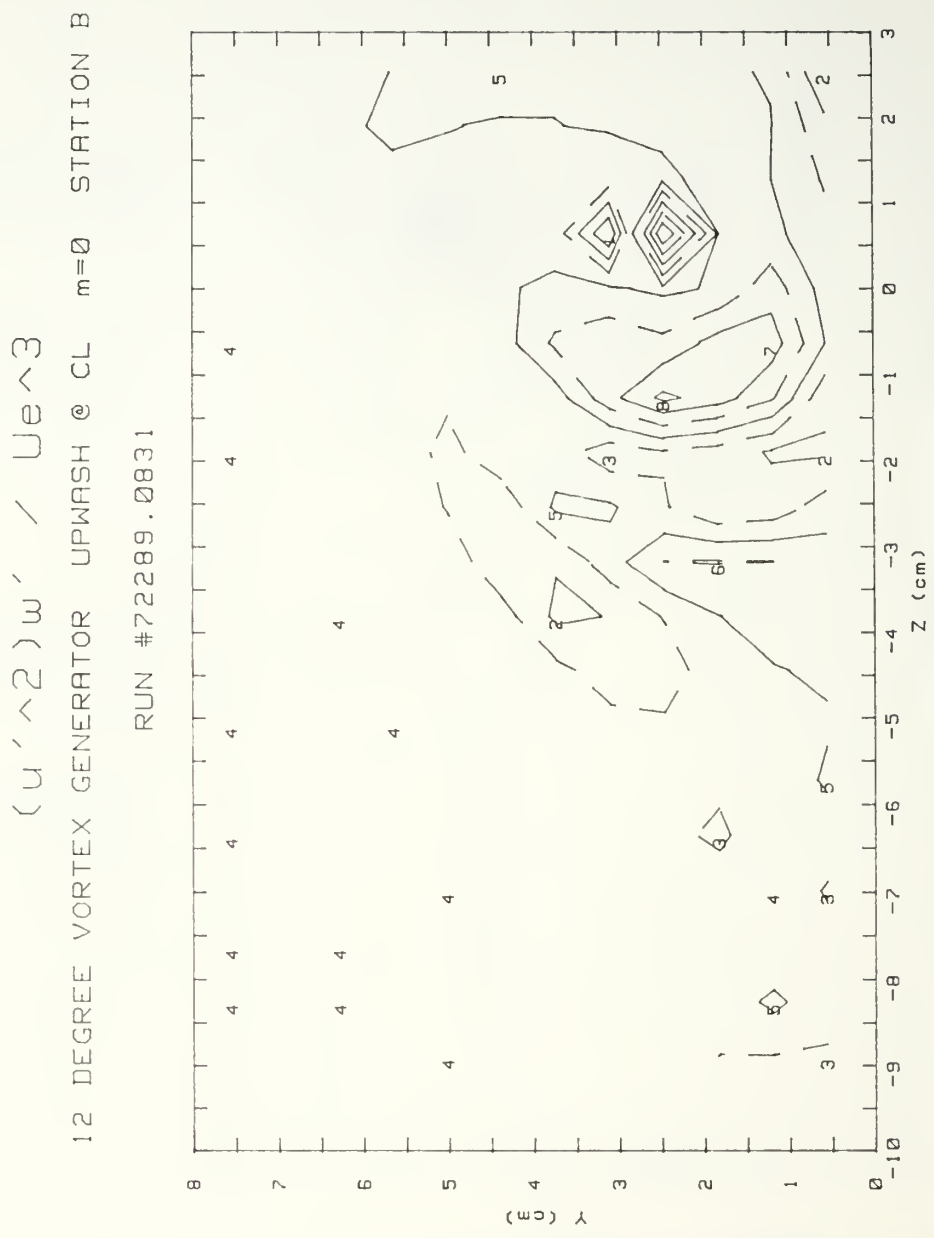

Figure 147. $\overline{u'^2w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

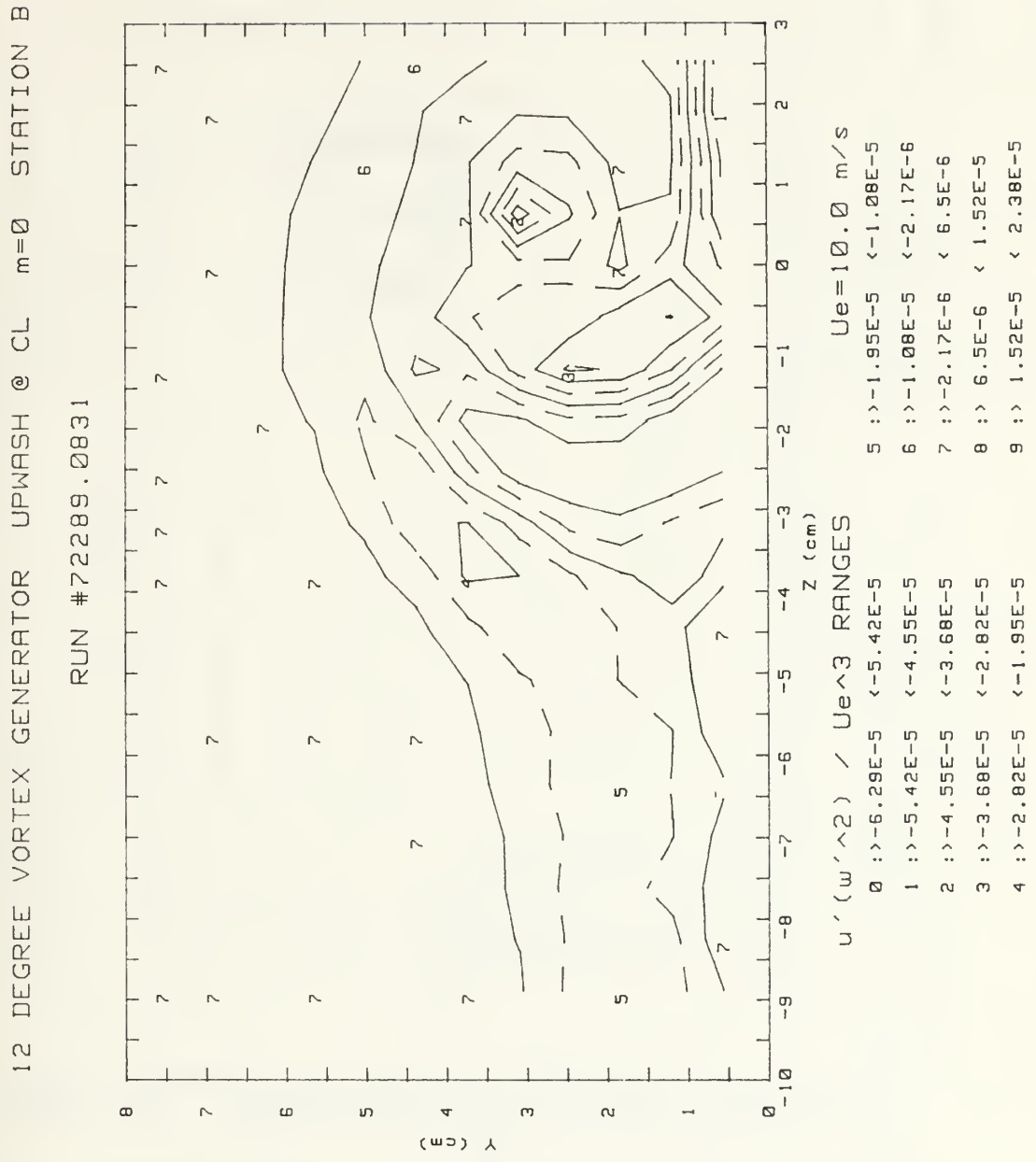

Figure 148. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

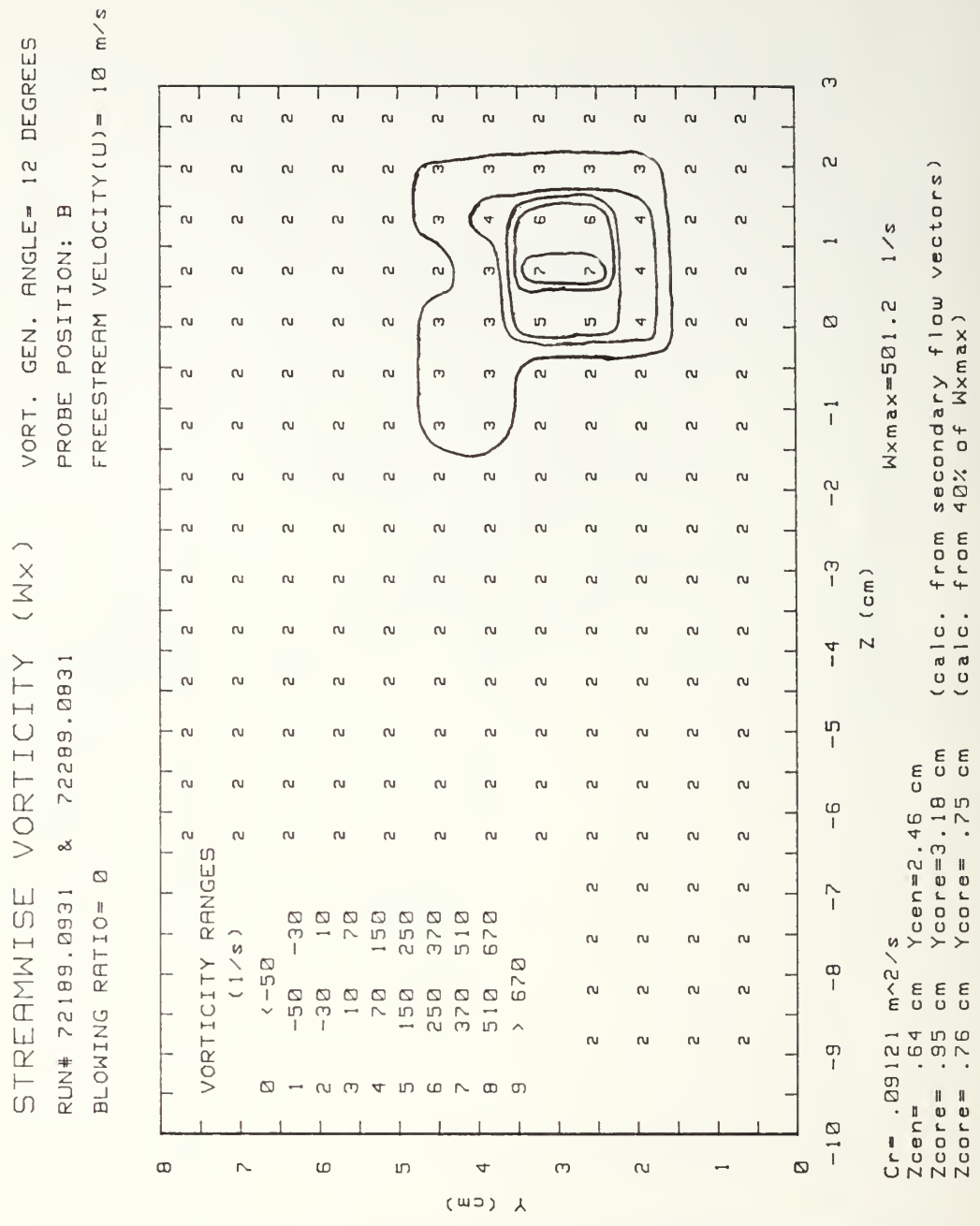

Figure 149. Streamwise Vorticity (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0, Δ = 0.25)

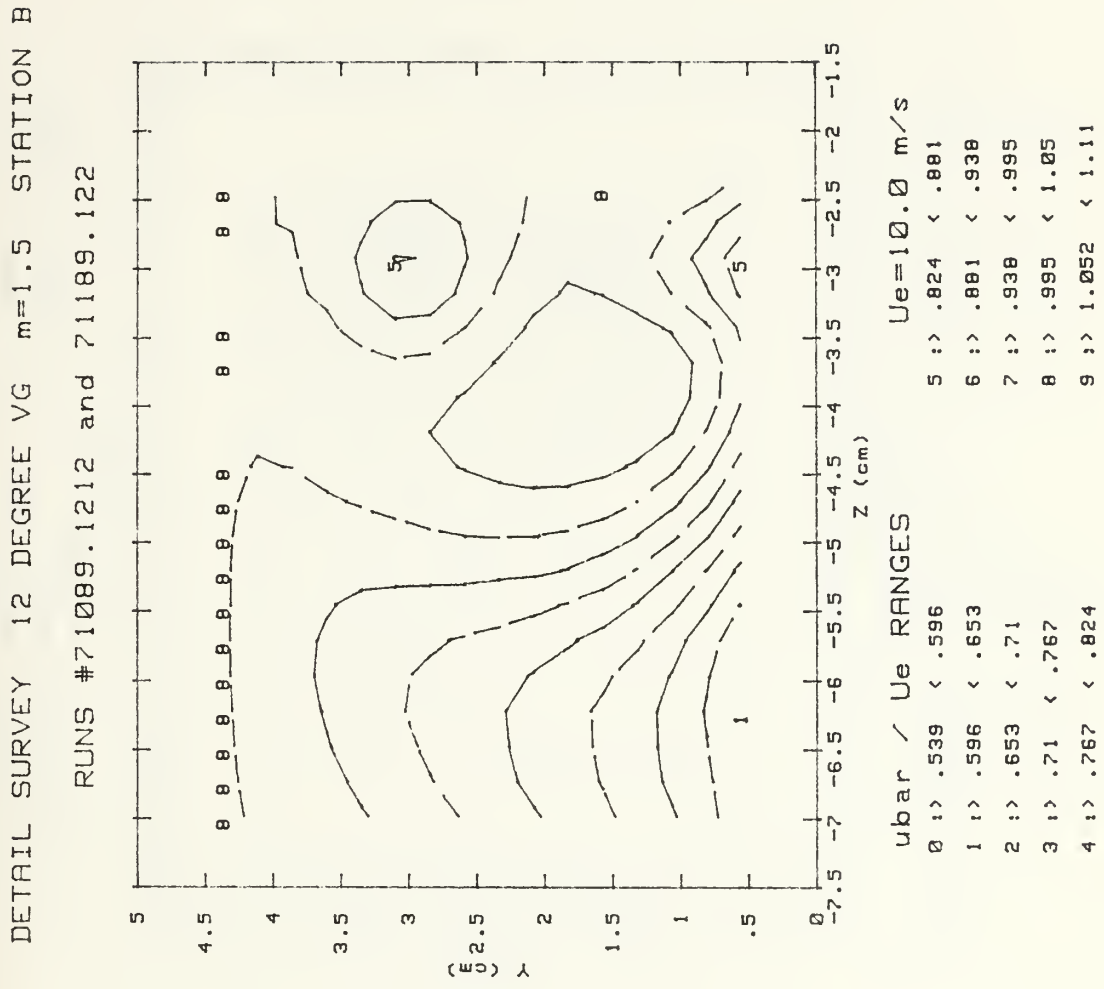

Figure 150. $\bar{u}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

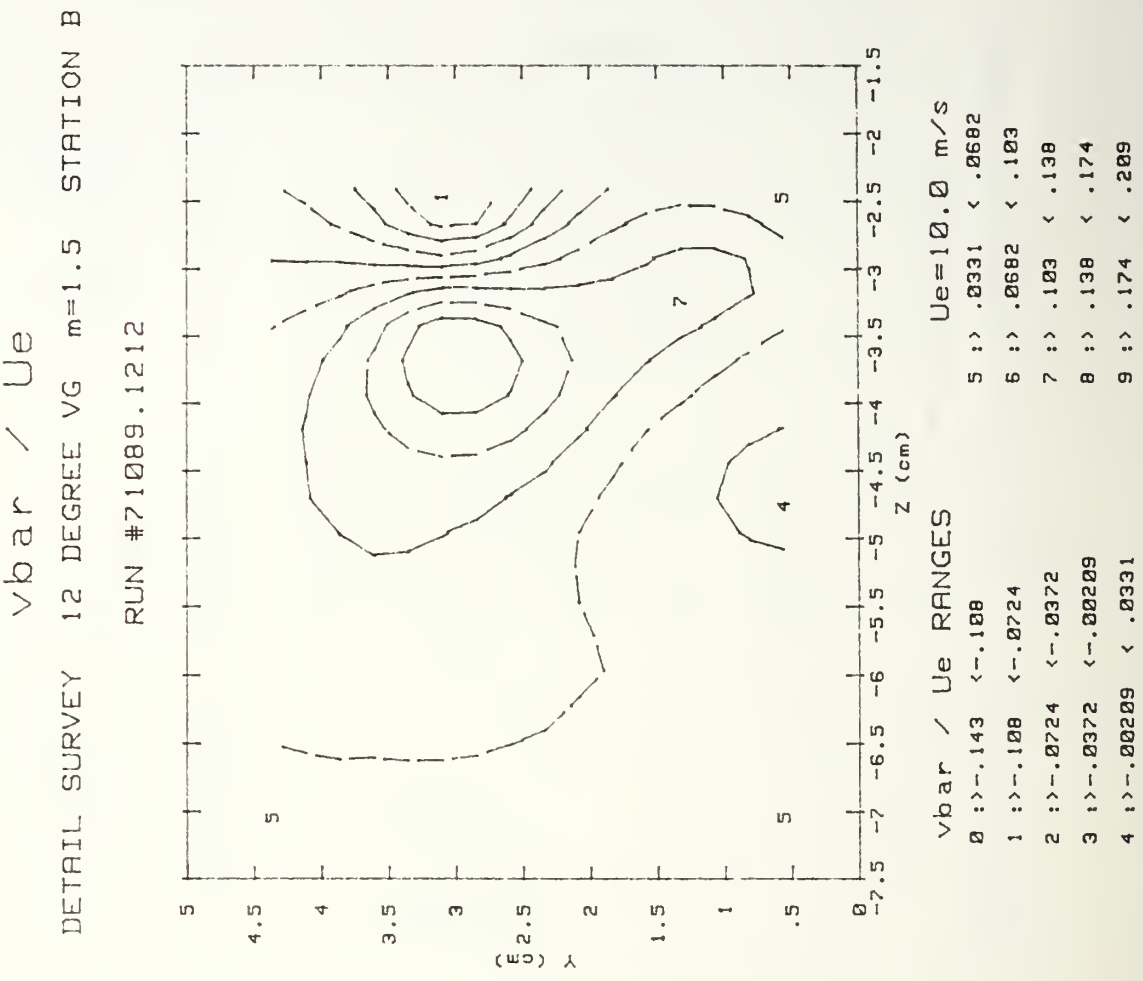

Figure 151. $\bar{v}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

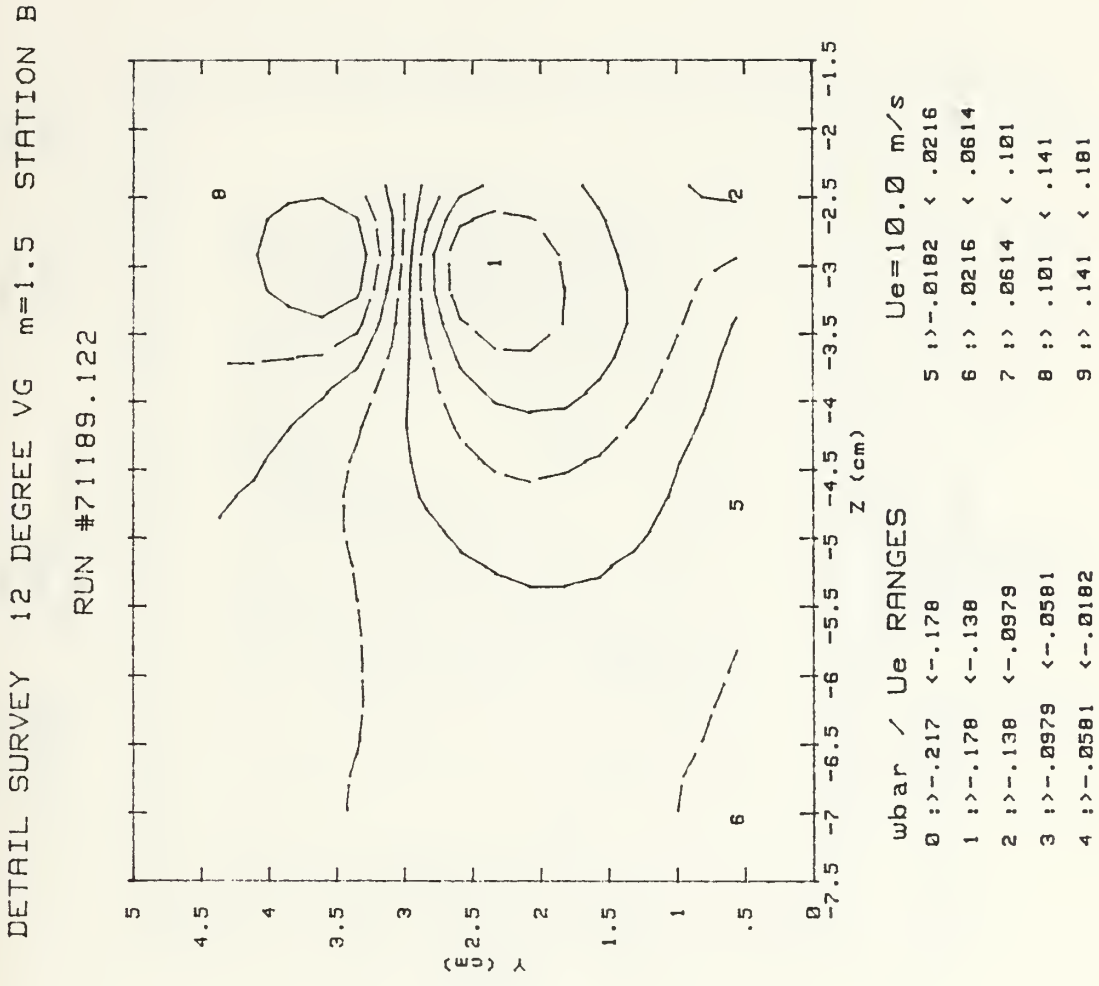

Figure 152. $\overline{w}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

Figure 153. $\overline{u'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

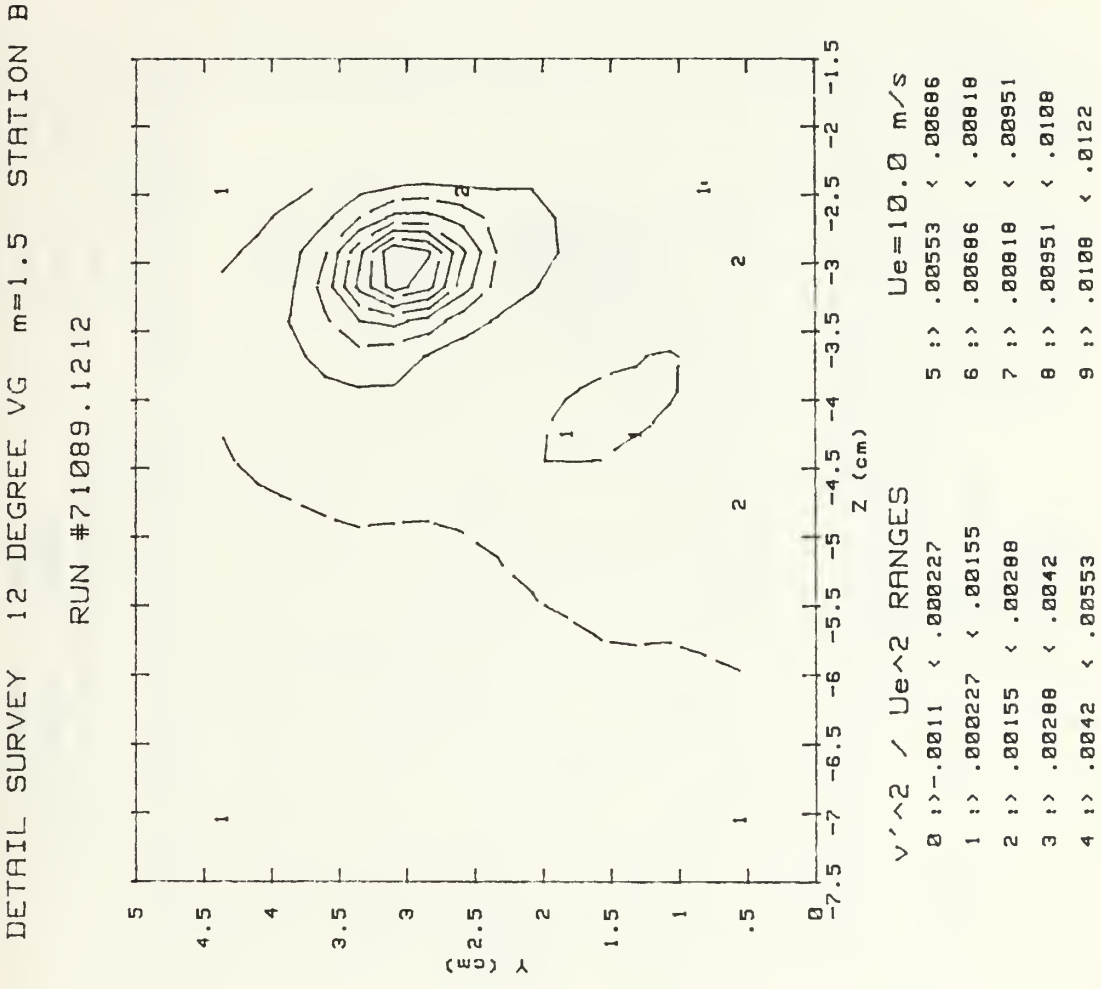

Figure 154. $\overline{v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

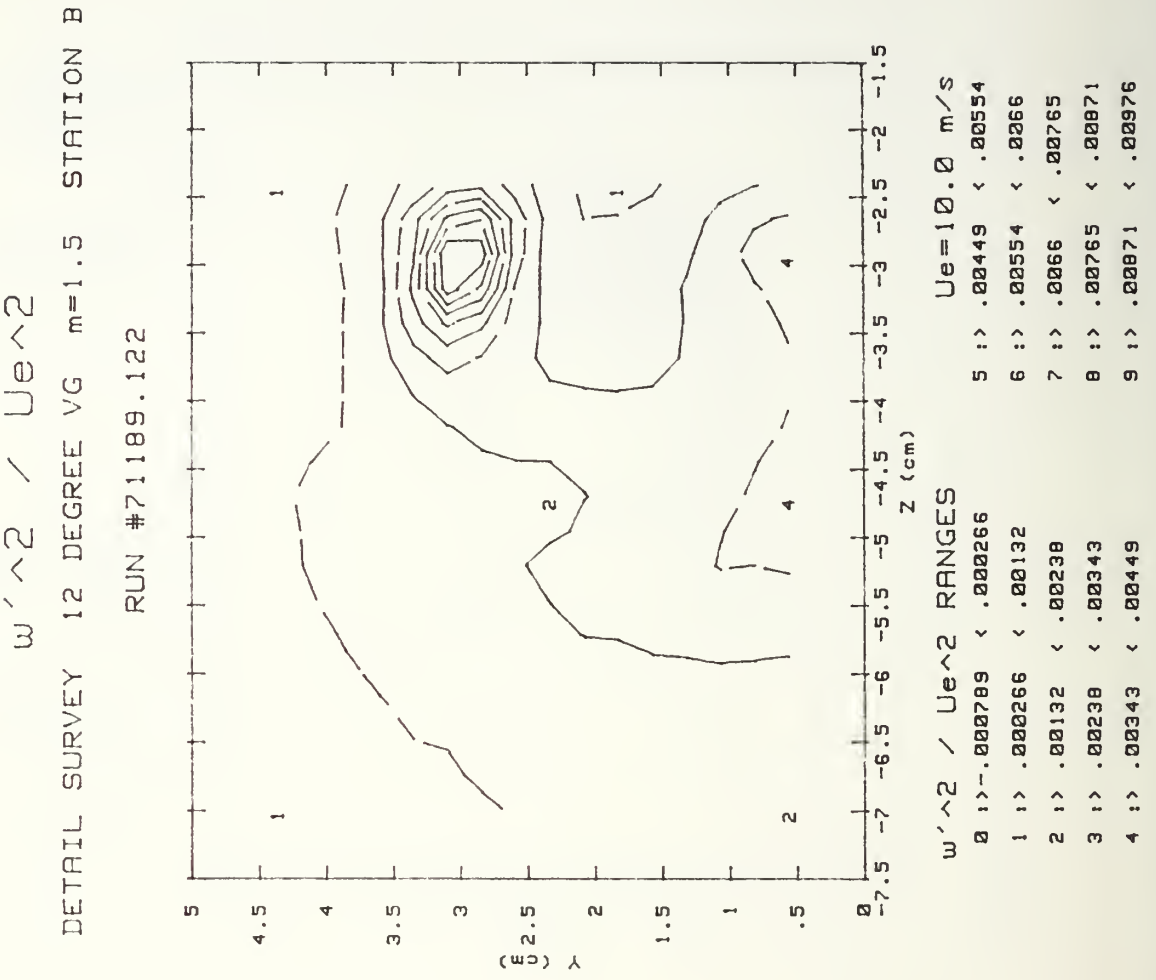

Figure 155. $\overline{w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

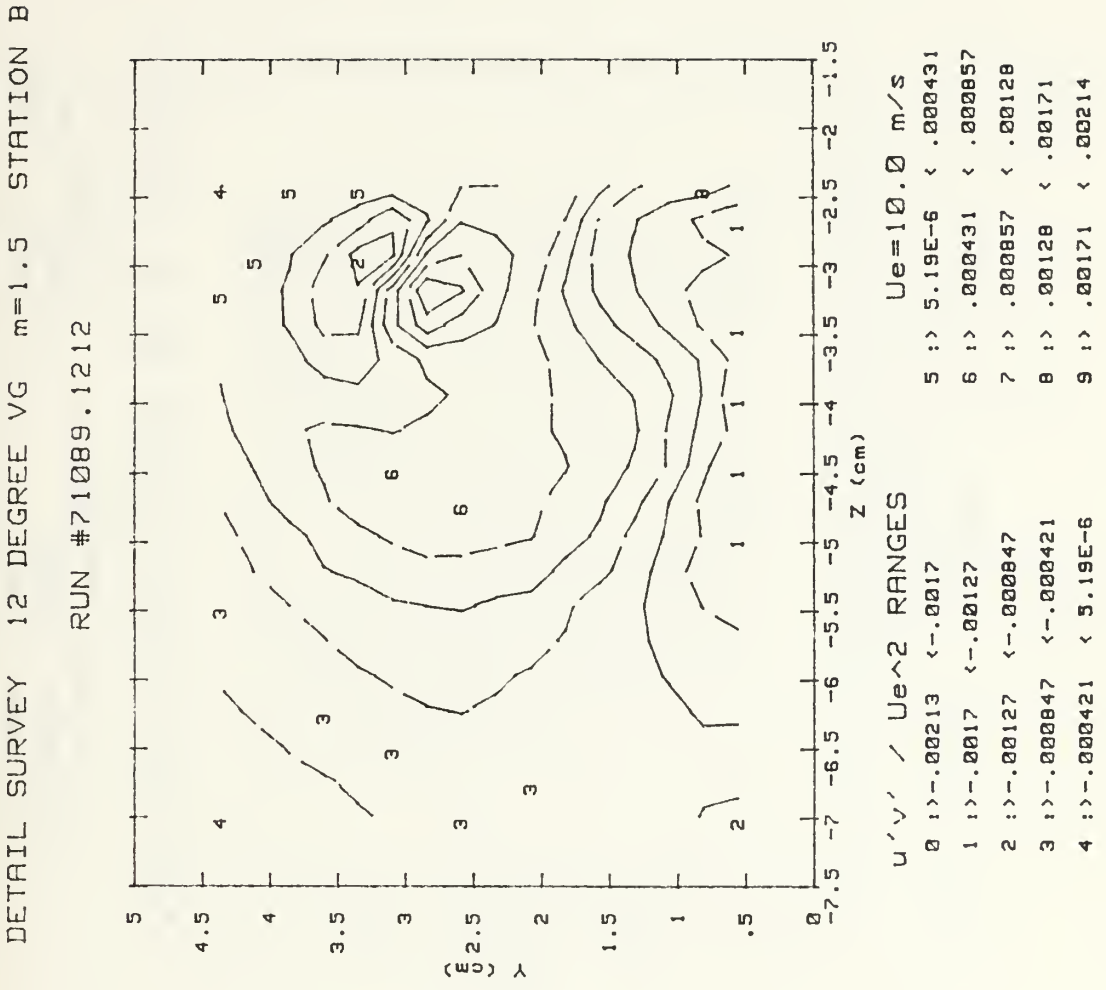

Figure 156. $\overline{u'v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

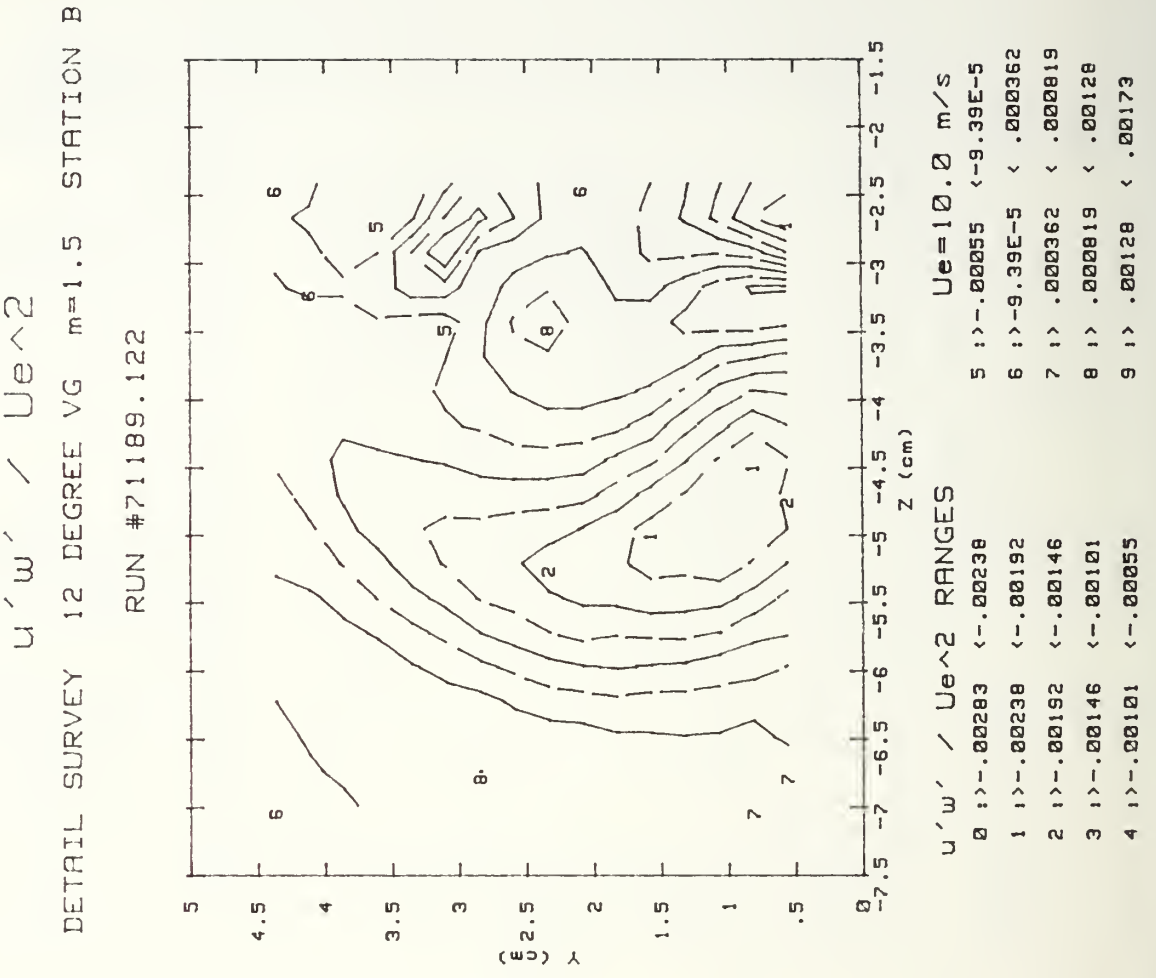

Figure 157. $\overline{u'w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

Figure 158. $\overline{u'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

Figure 159. $\overline{v'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

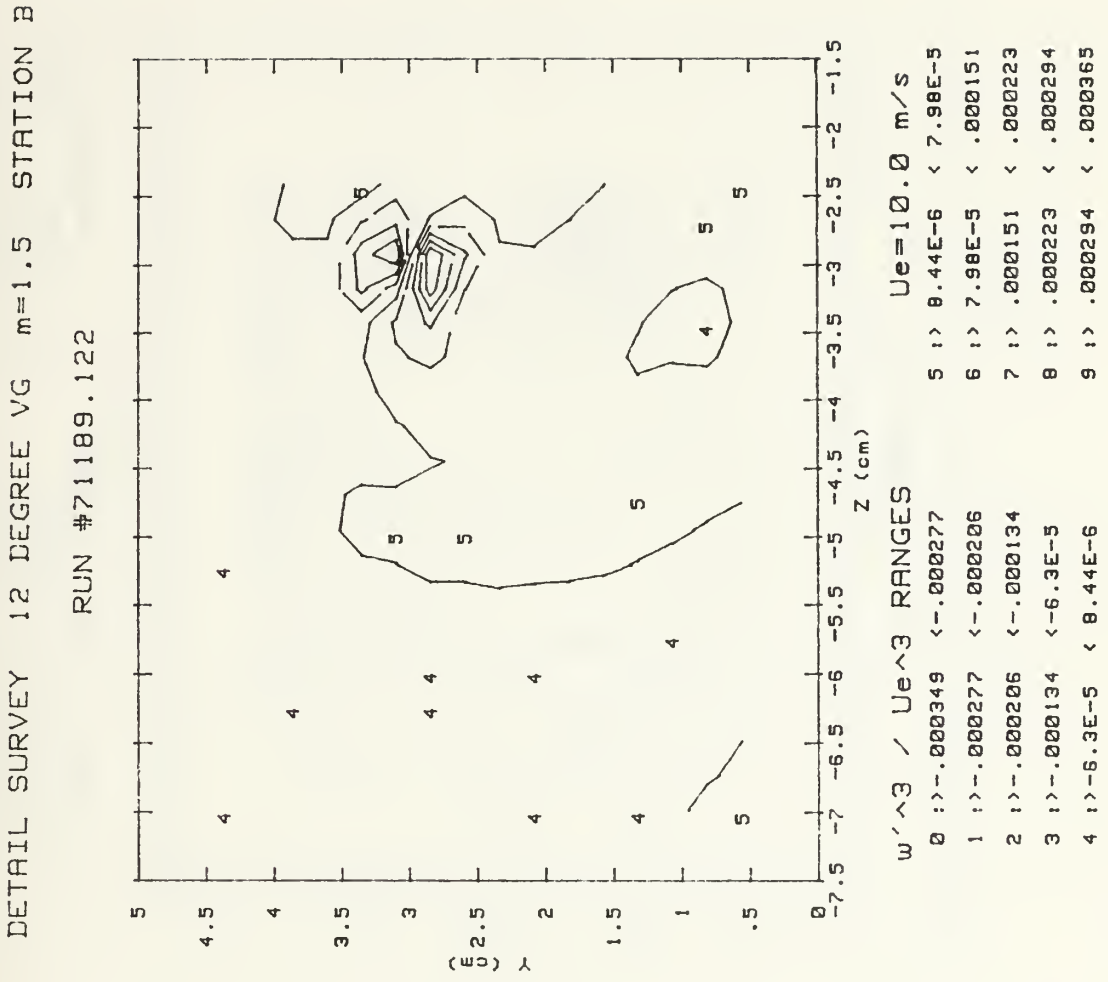

Figure 160. $\overline{w'^3}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

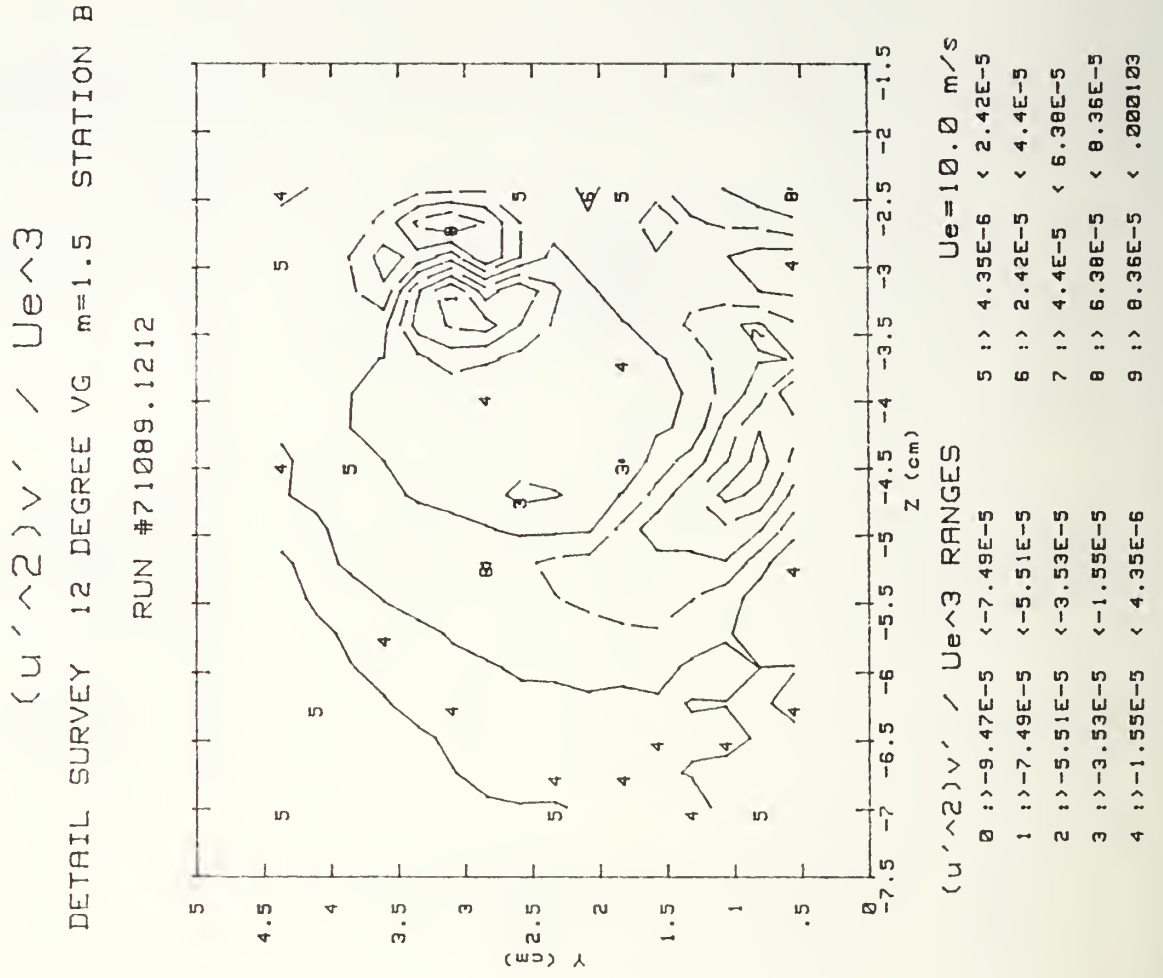

Figure 161. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

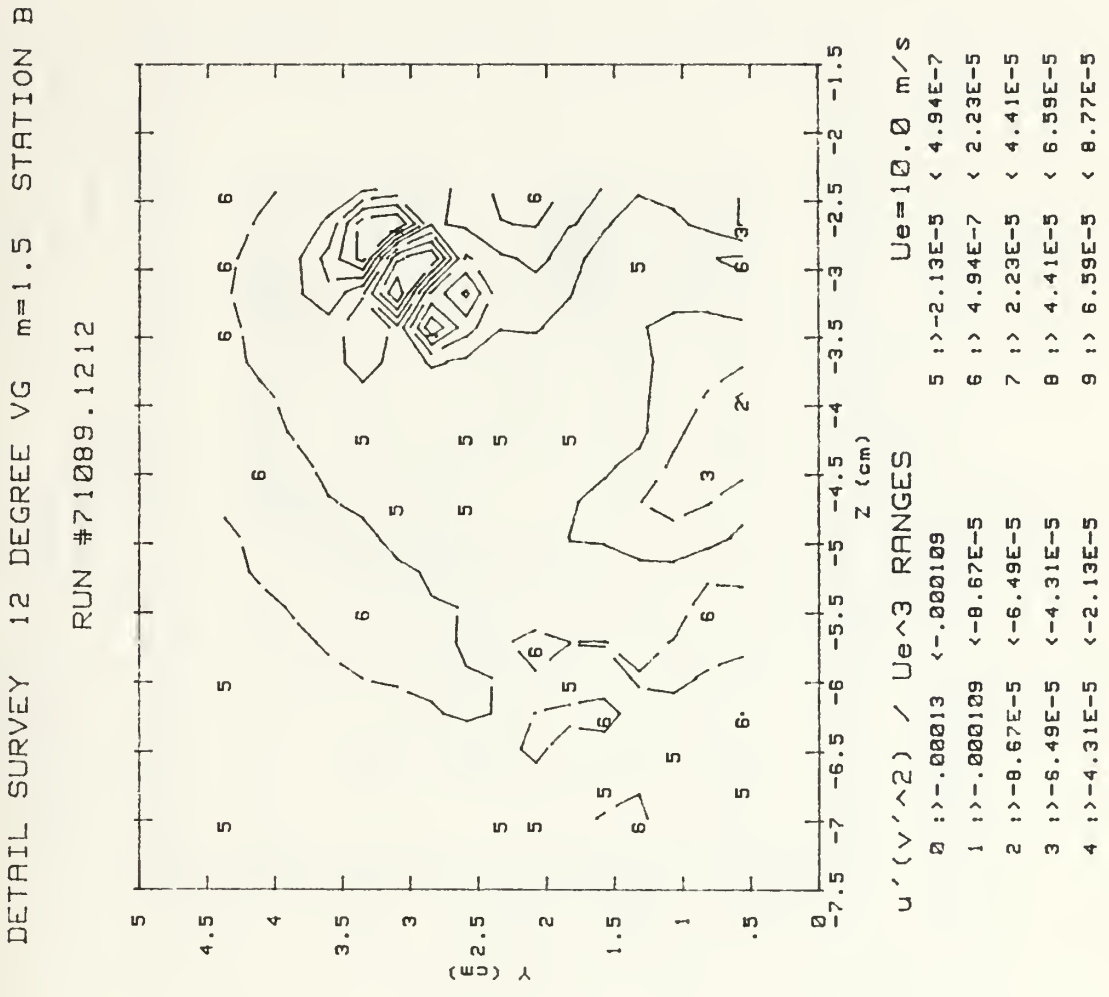

Figure 162. $\overline{u'v'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

Figure 163. $\overline{u'^2w'}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

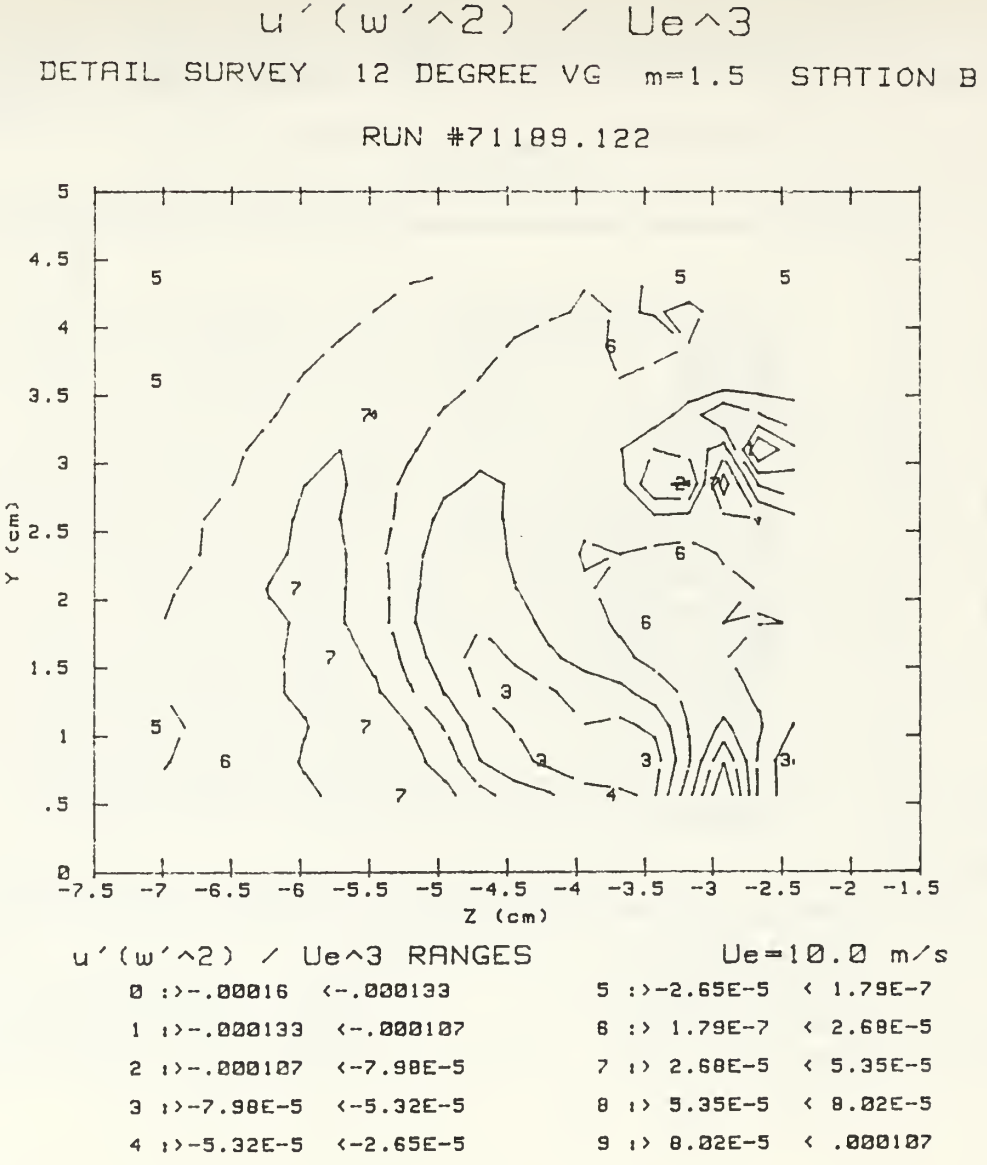

Figure 164. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

Figure 165. Streamwise Vorticity (Boundary Layer w/vortex, Downwash @ Centerline, Station B, m = 1.5, Δ = 0.10)

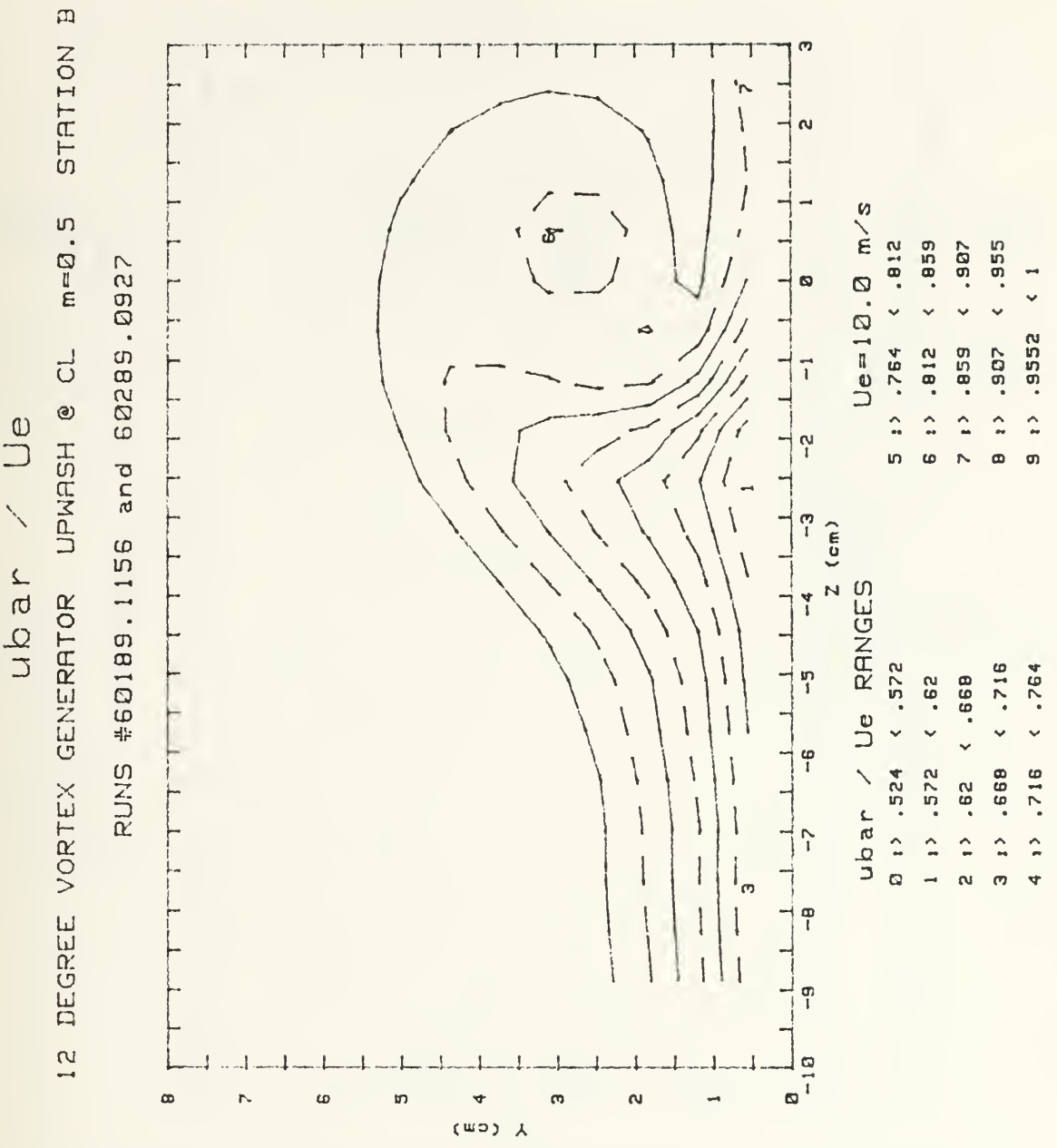

Figure 166. $\bar{u}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

Figure 167. $\bar{v}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

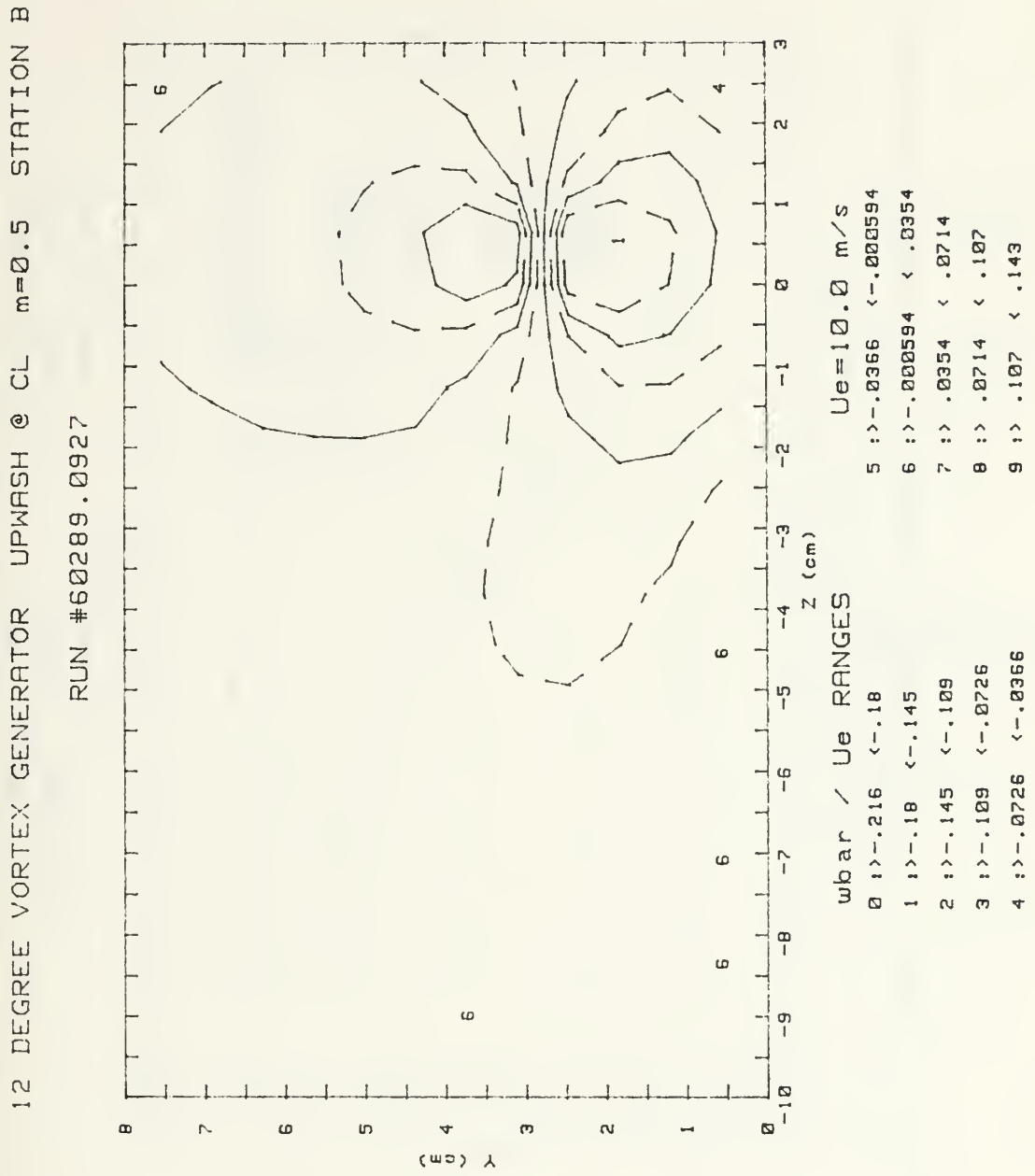

Figure 168. $\overline{w}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

Figure 169. $\overline{u'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

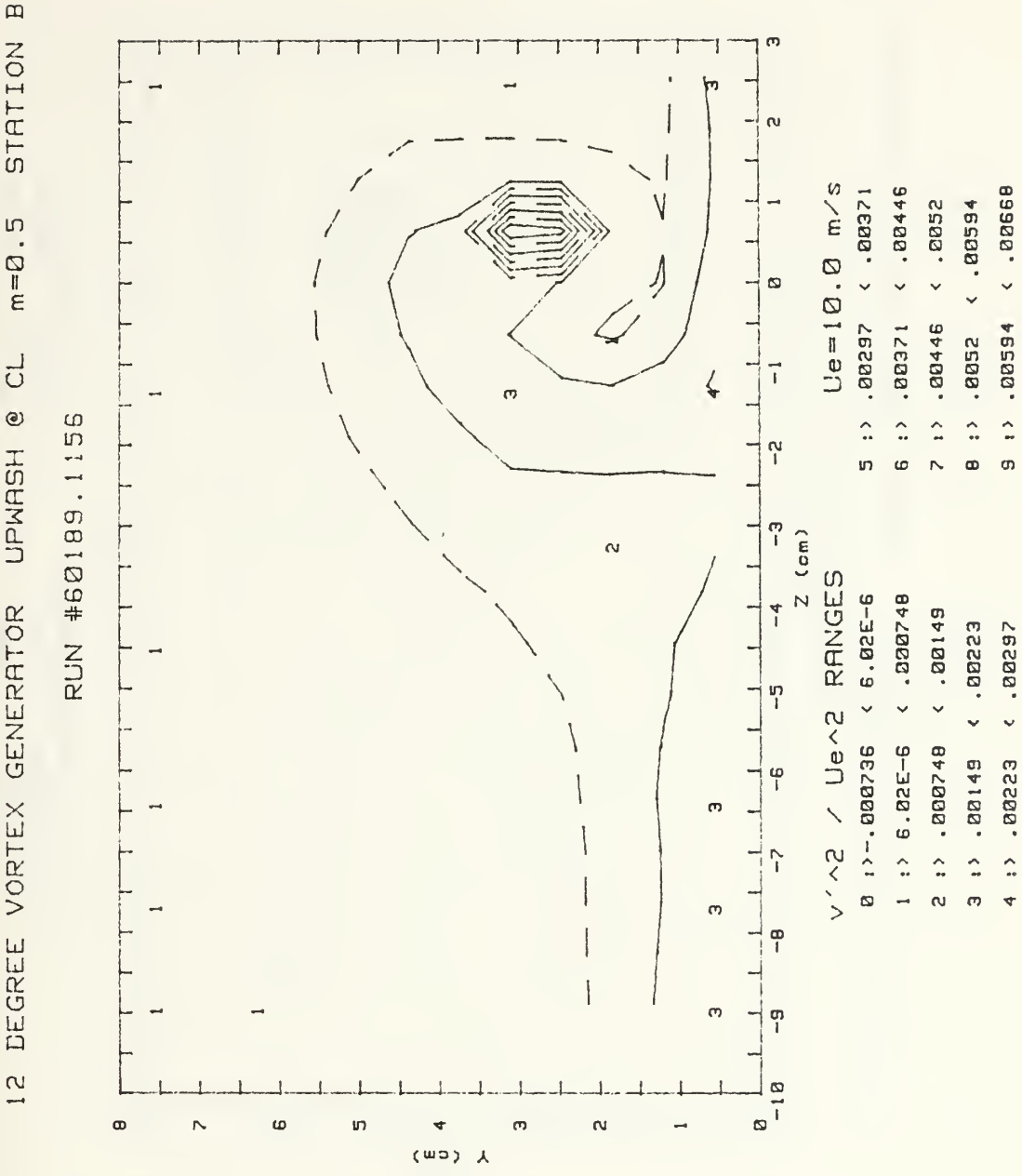

Figure 170. $\overline{v'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

Figure 171. $\overline{w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

Figure 172. $\overline{u'v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

Figure 173. $\overline{u'w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

Figure 174. $\overline{u'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

Figure 175. $\overline{v'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

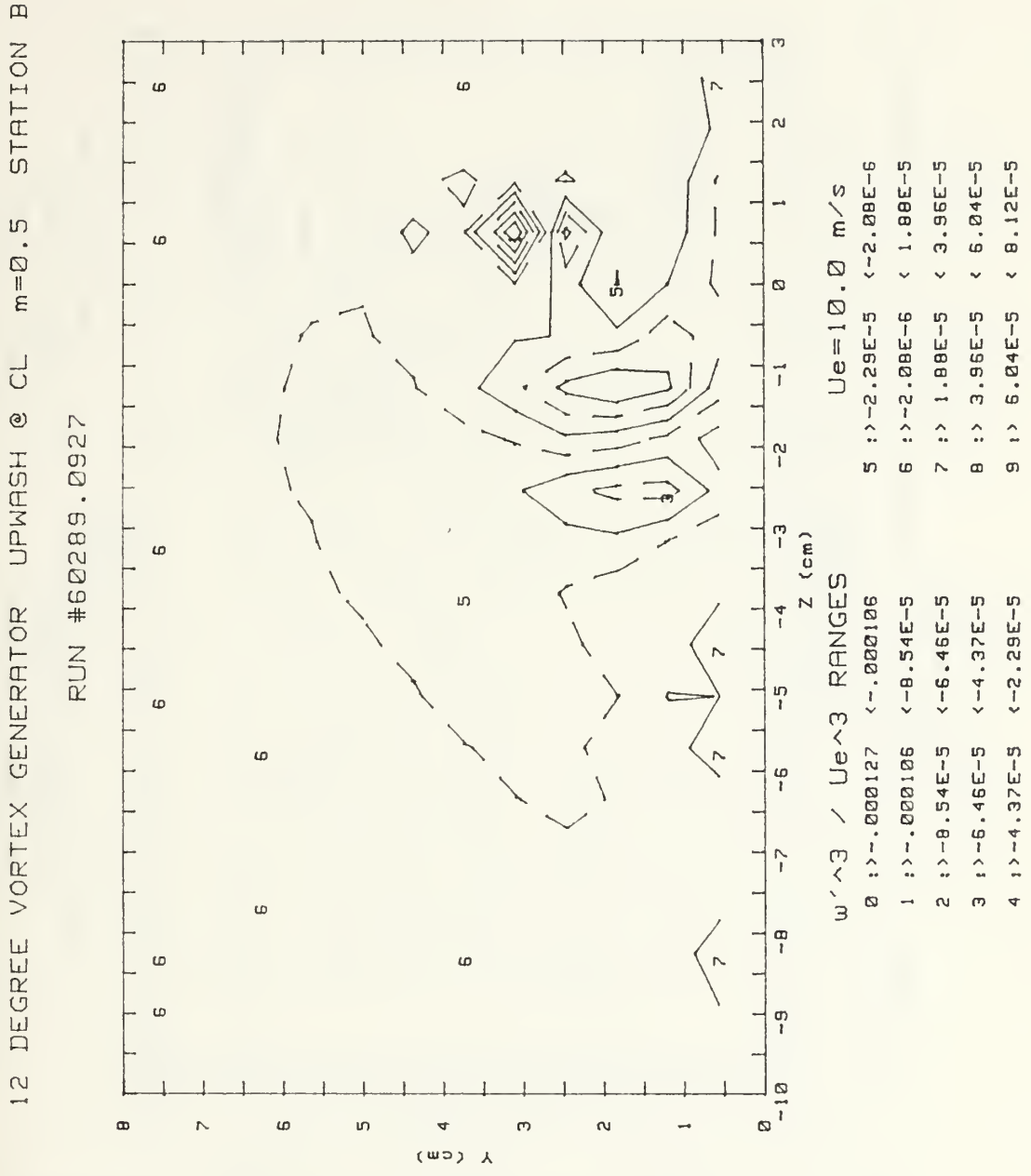

Figure 176. $\overline{w'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

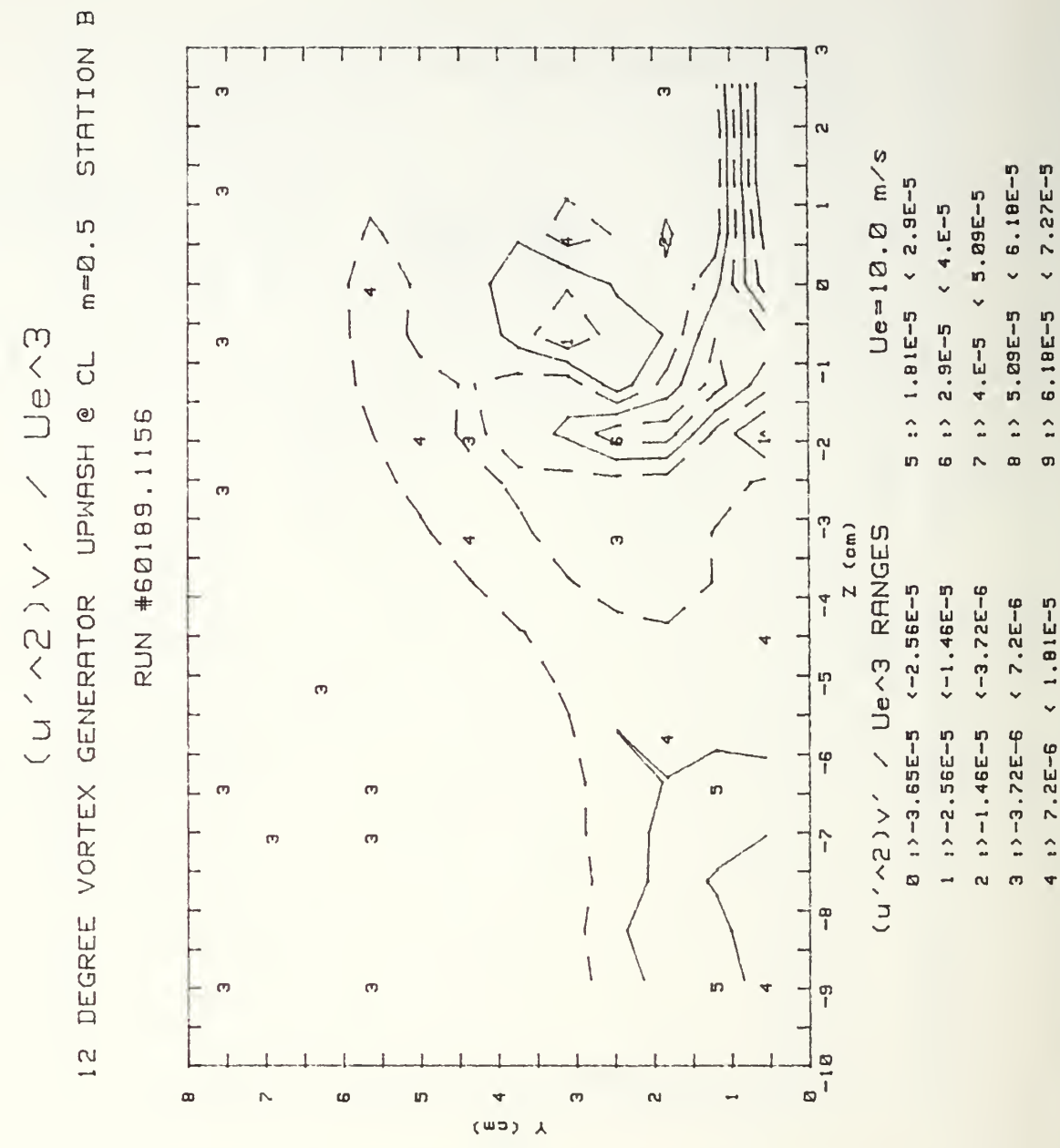

Figure 177. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

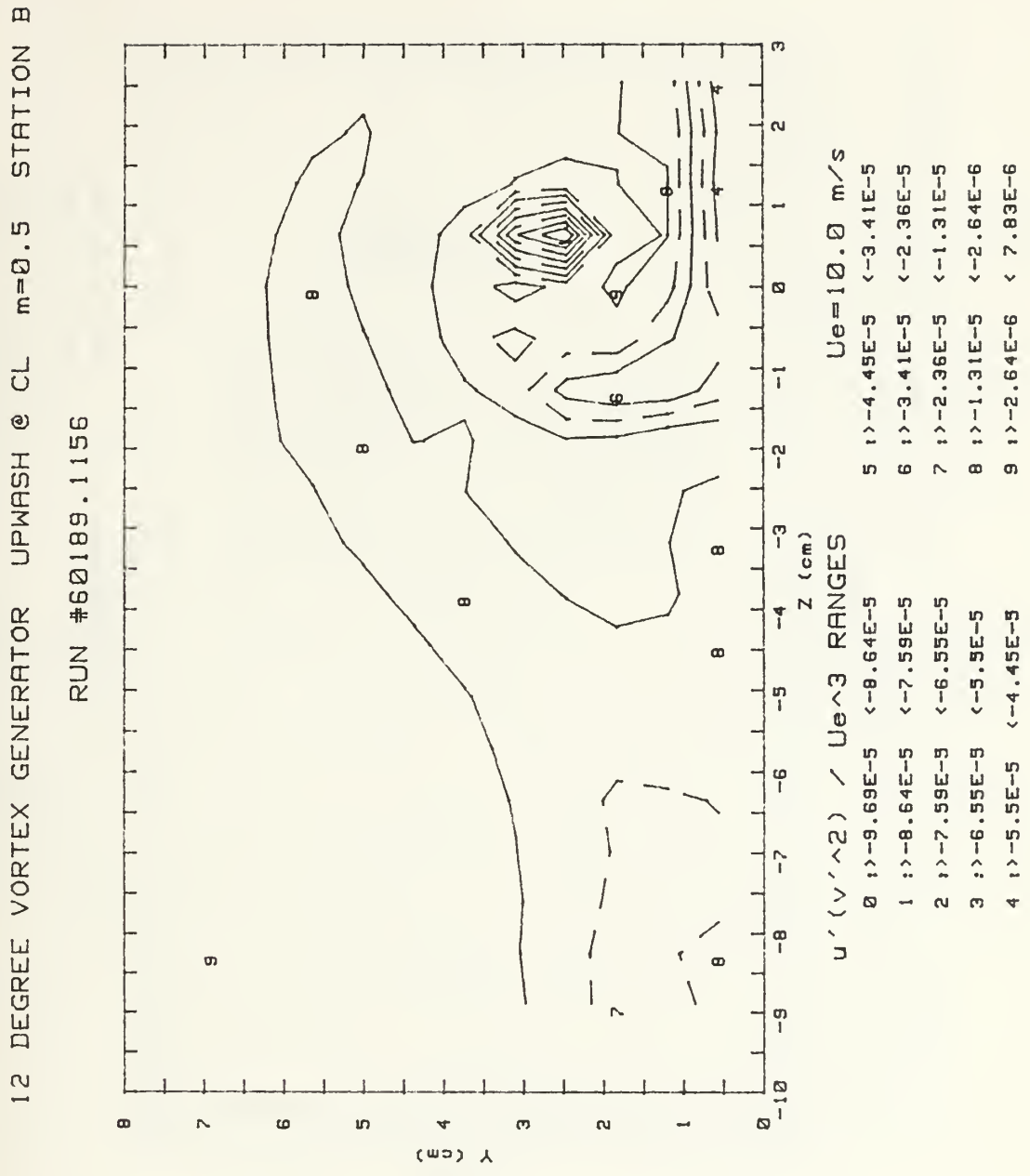

Figure 178. $\overline{u'v'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

Figure 179. $\overline{u'^2w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

Figure 180. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

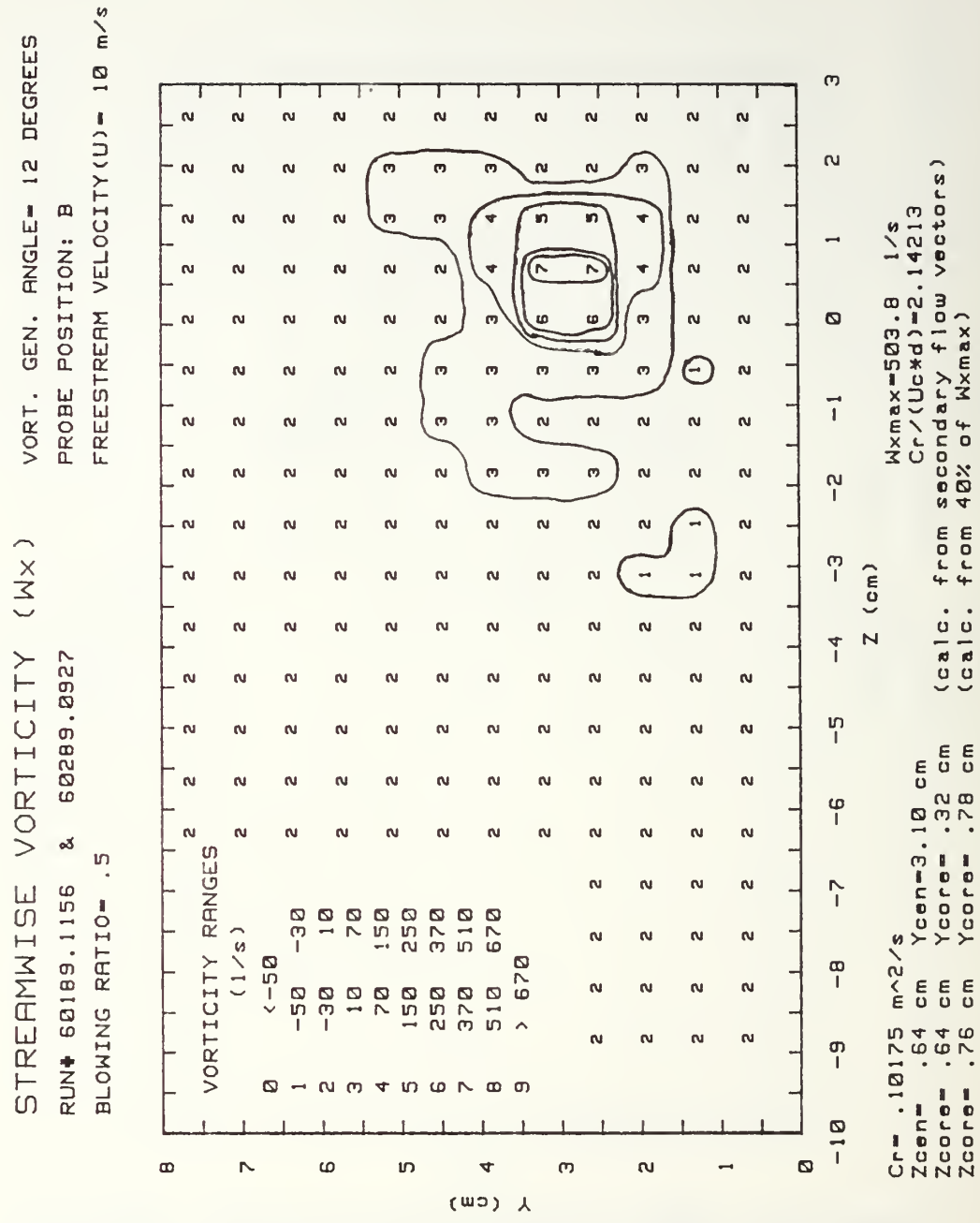

Figure 181. Streamwise Vorticity (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 0.5, Δ = 0.25)

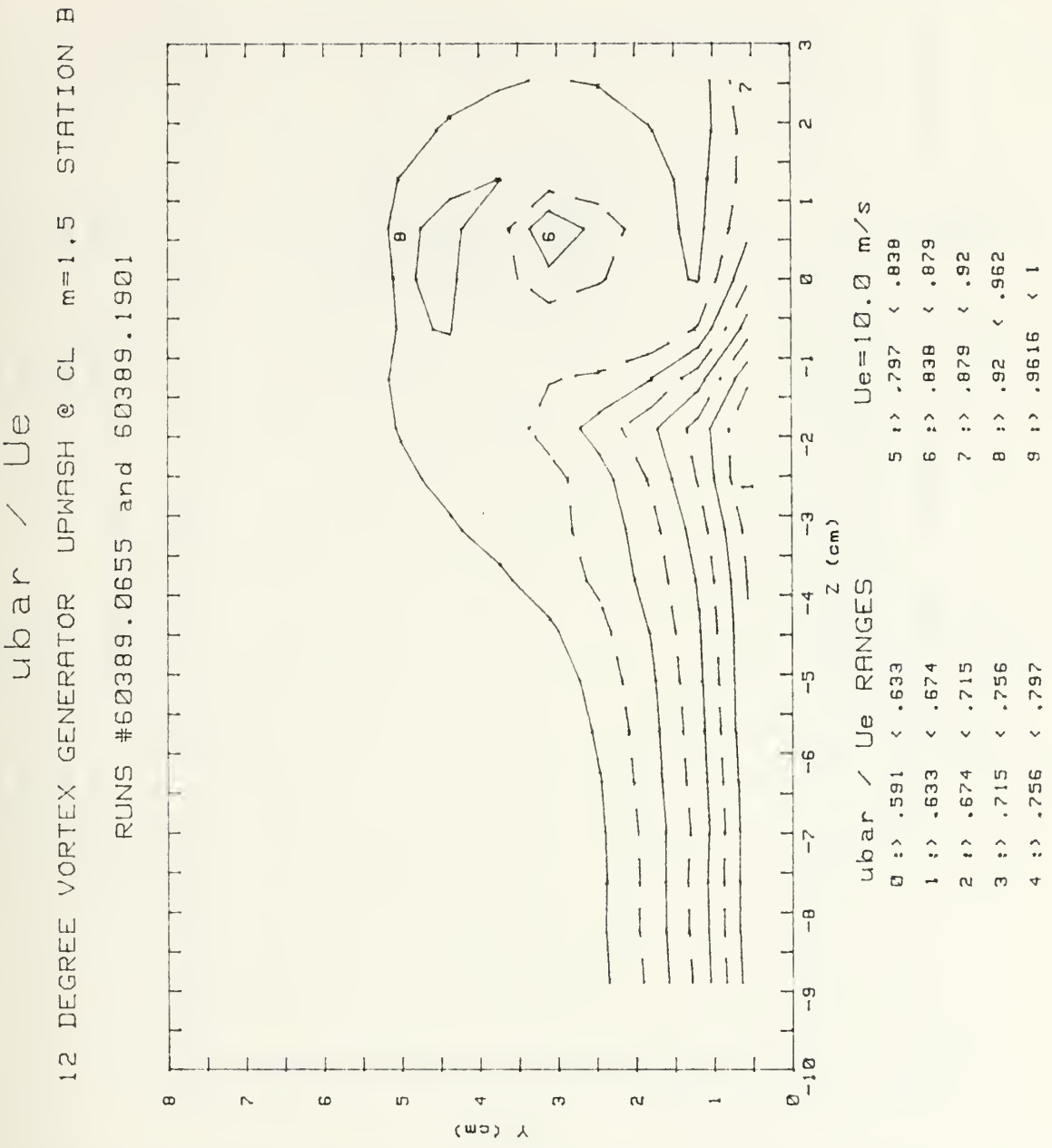

Figure 182. $\overline{u}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

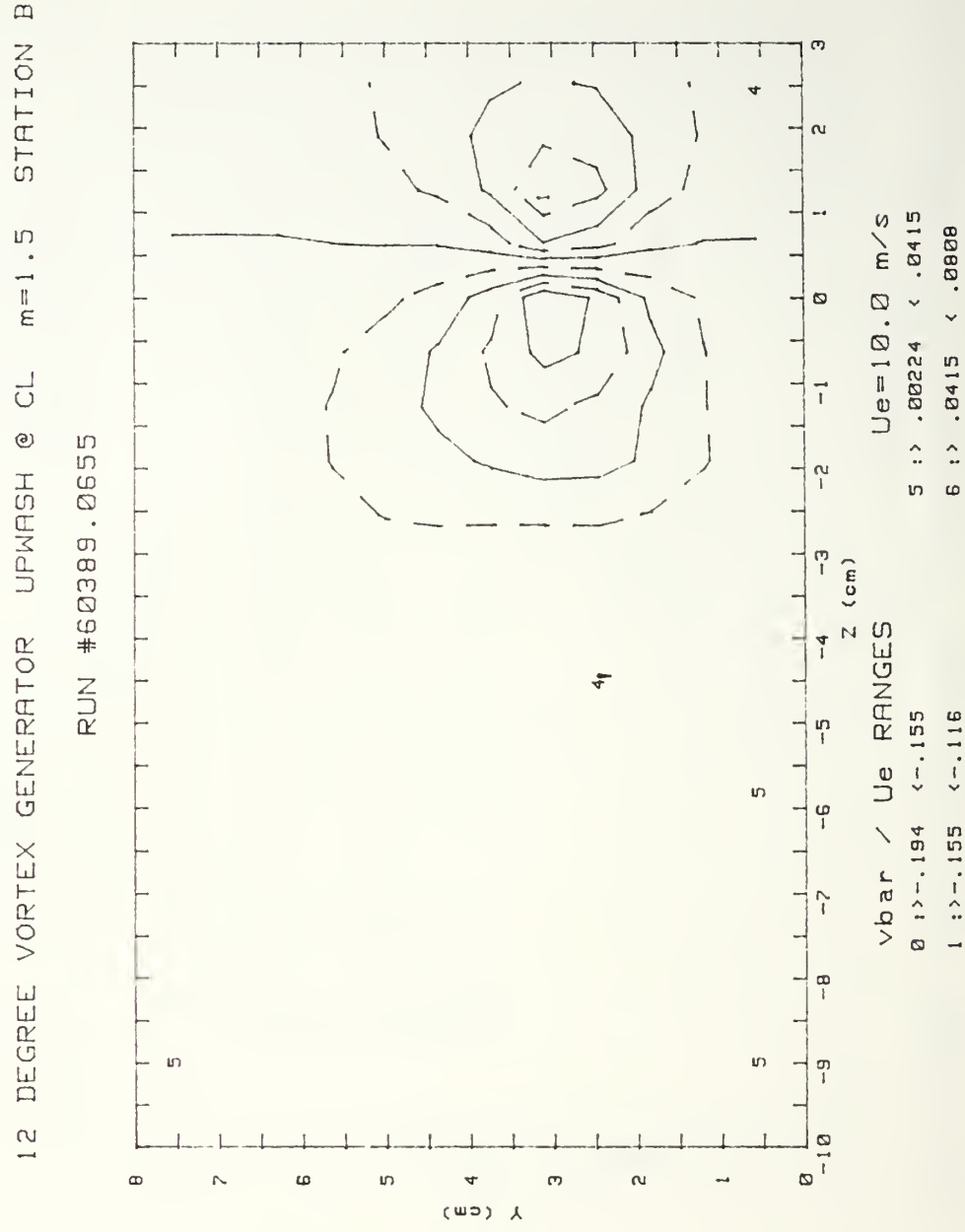

Figure 183. $\bar{v}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

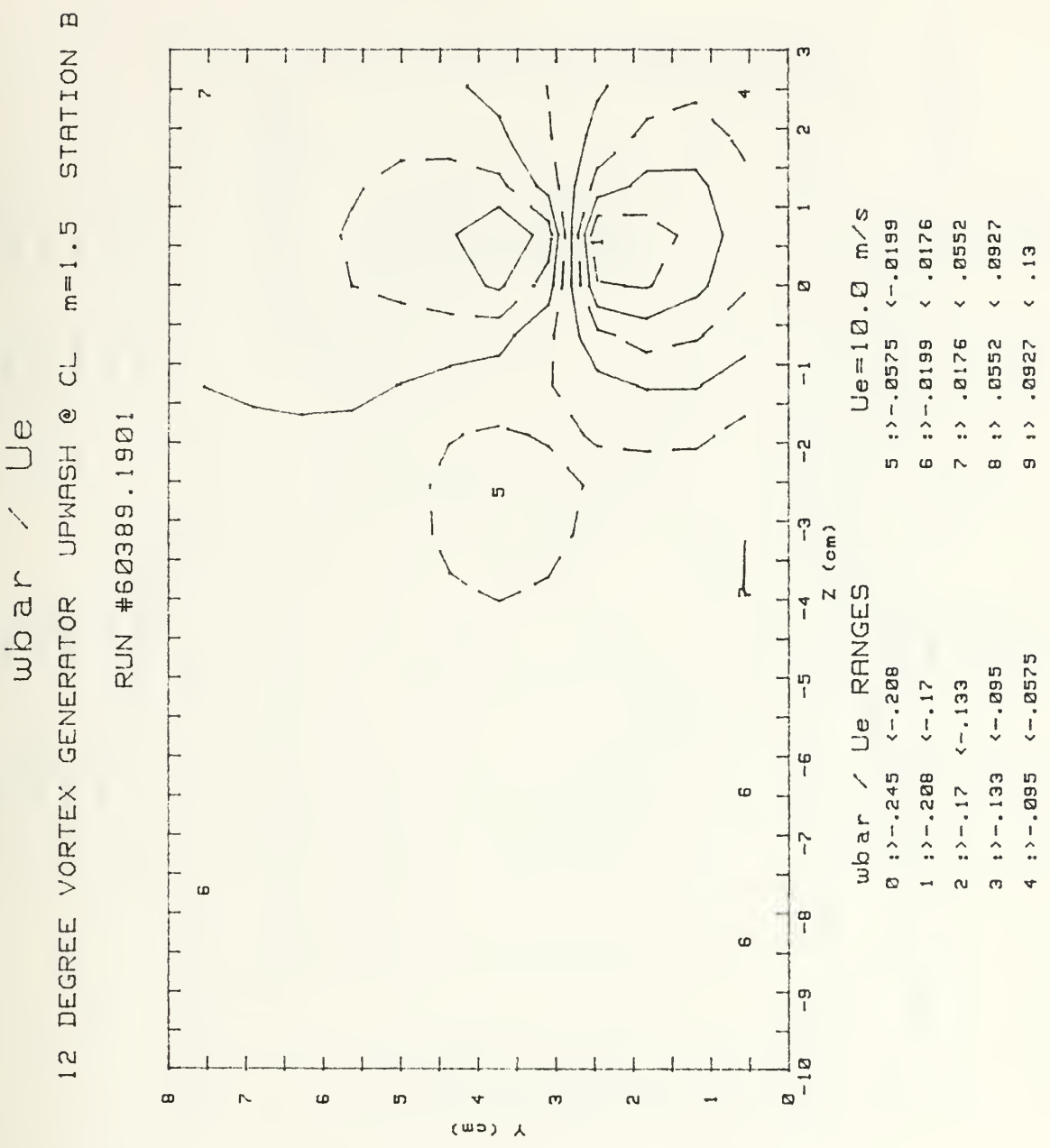

Figure 184. $\overline{w}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

Figure 185. $\overline{u'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

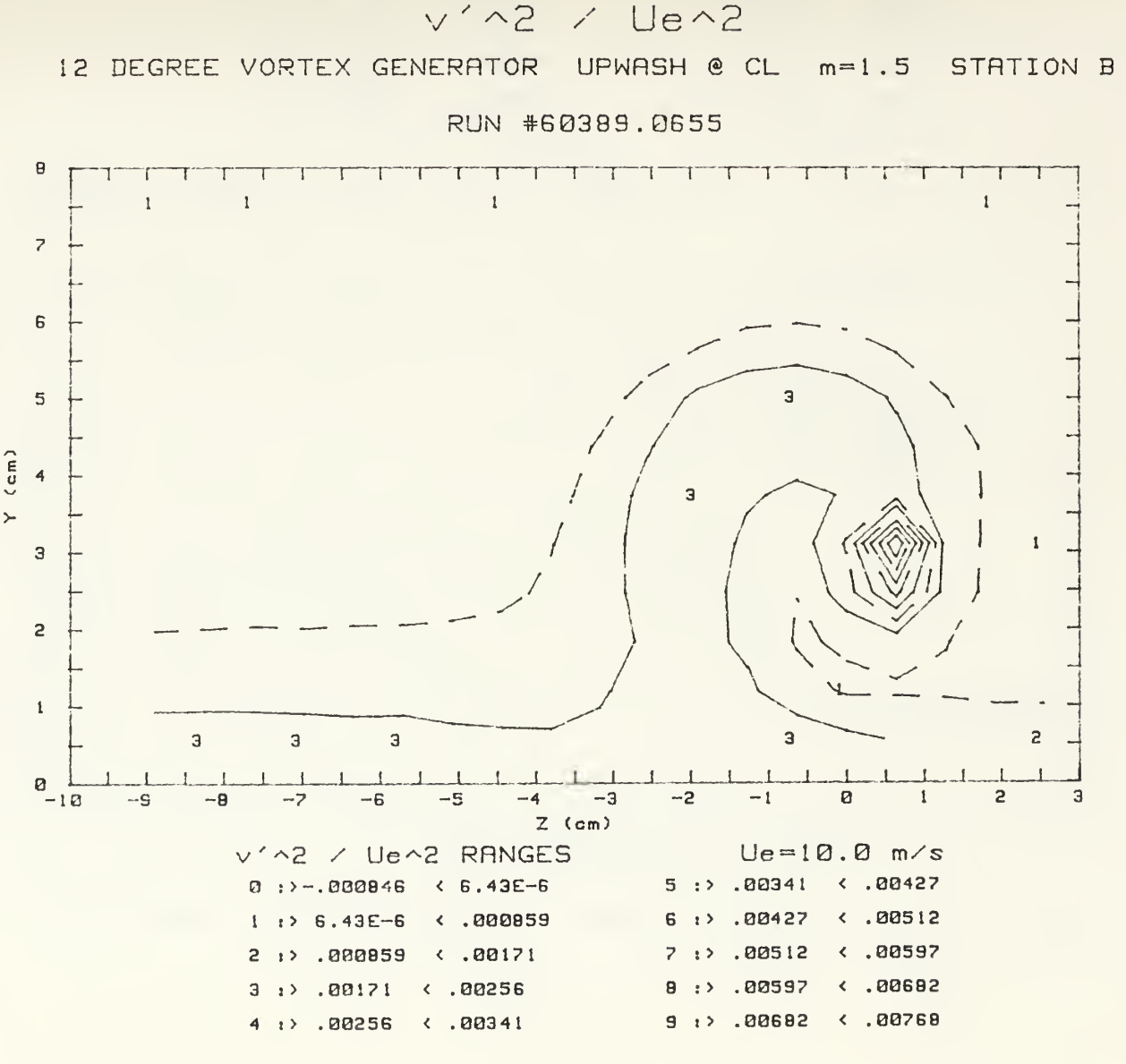

Figure 186. $\overline{v'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

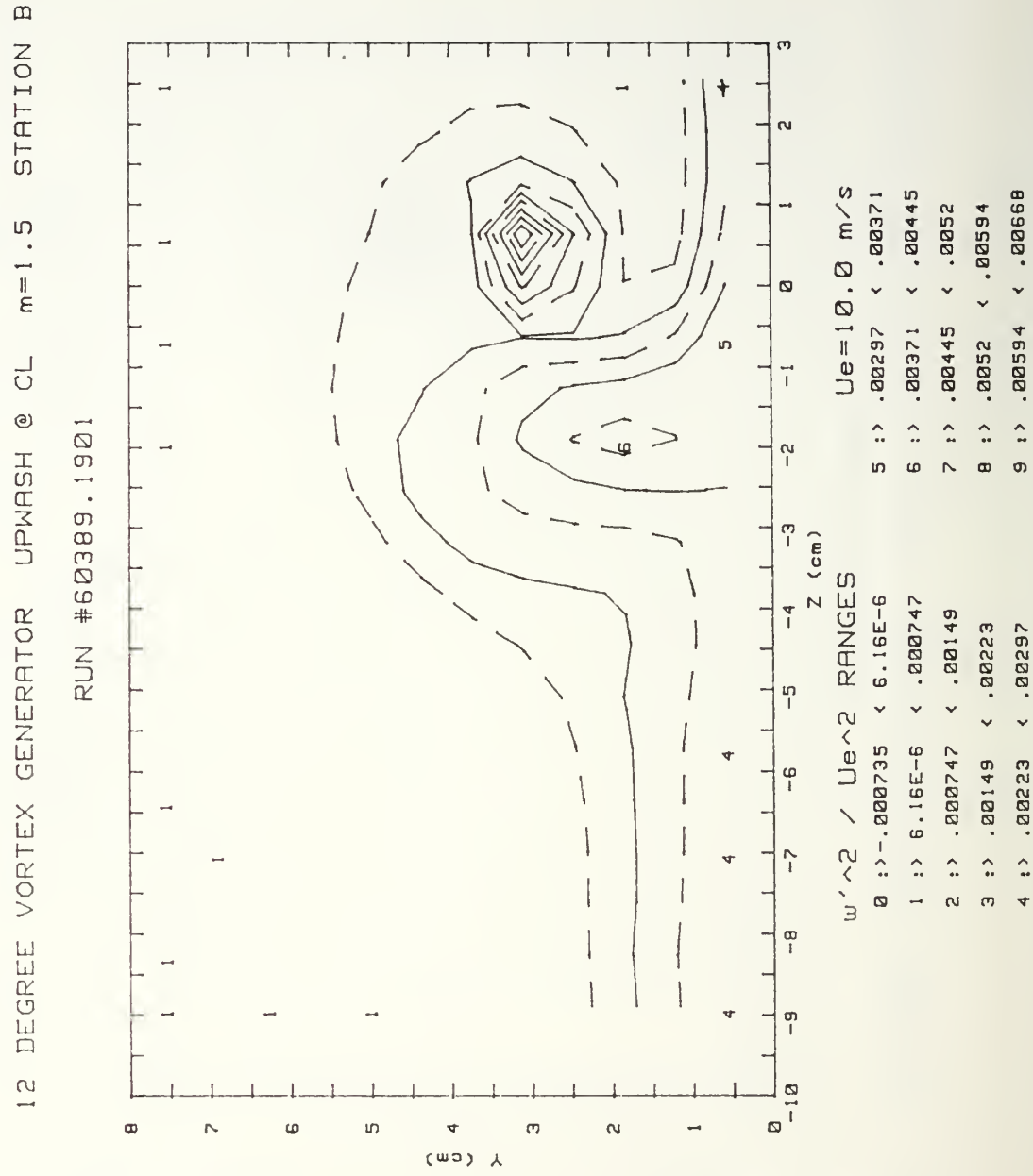

Figure 187. $\overline{w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

Figure 188. $\overline{u'v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

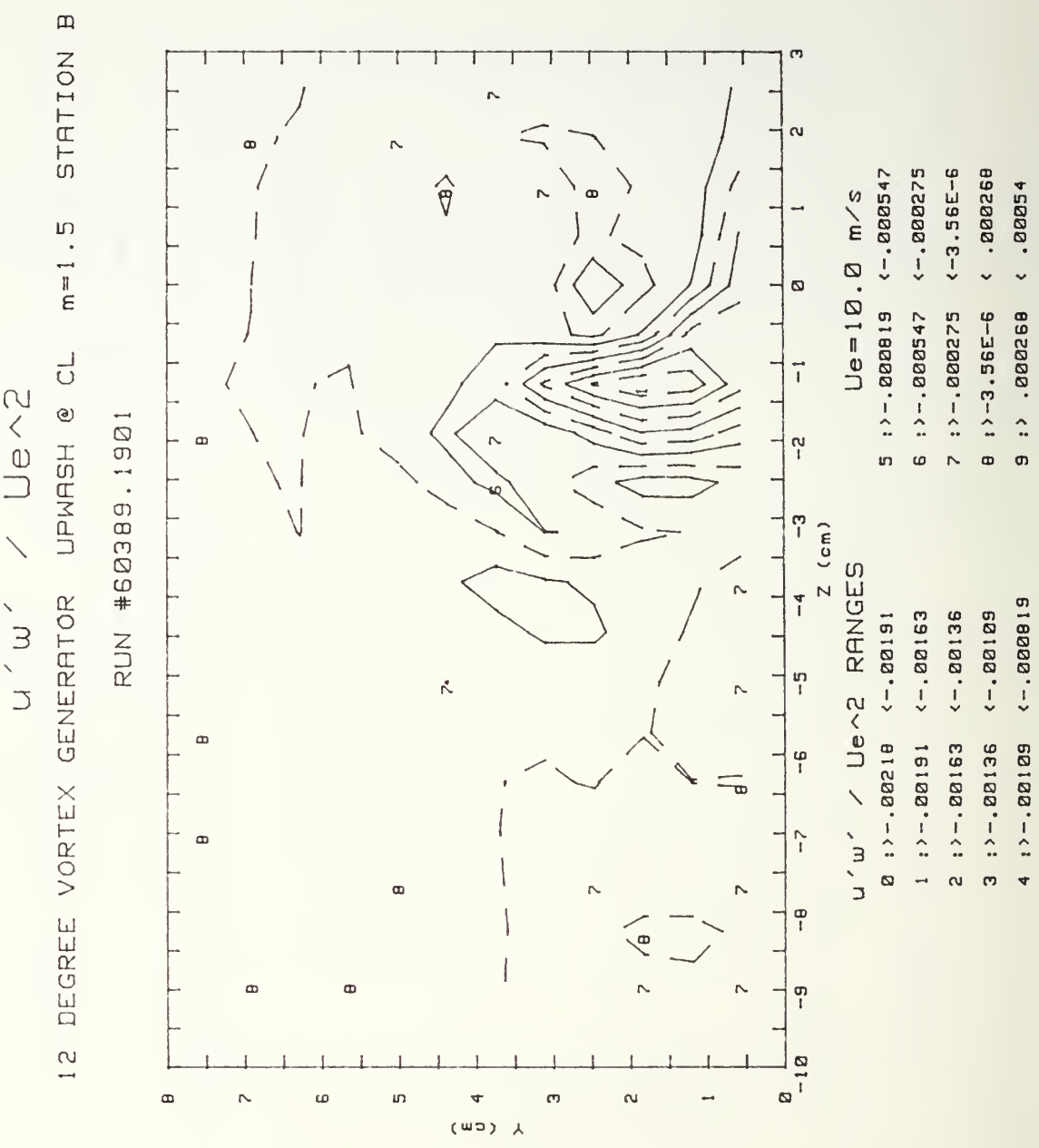

Figure 189. $\overline{u'w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

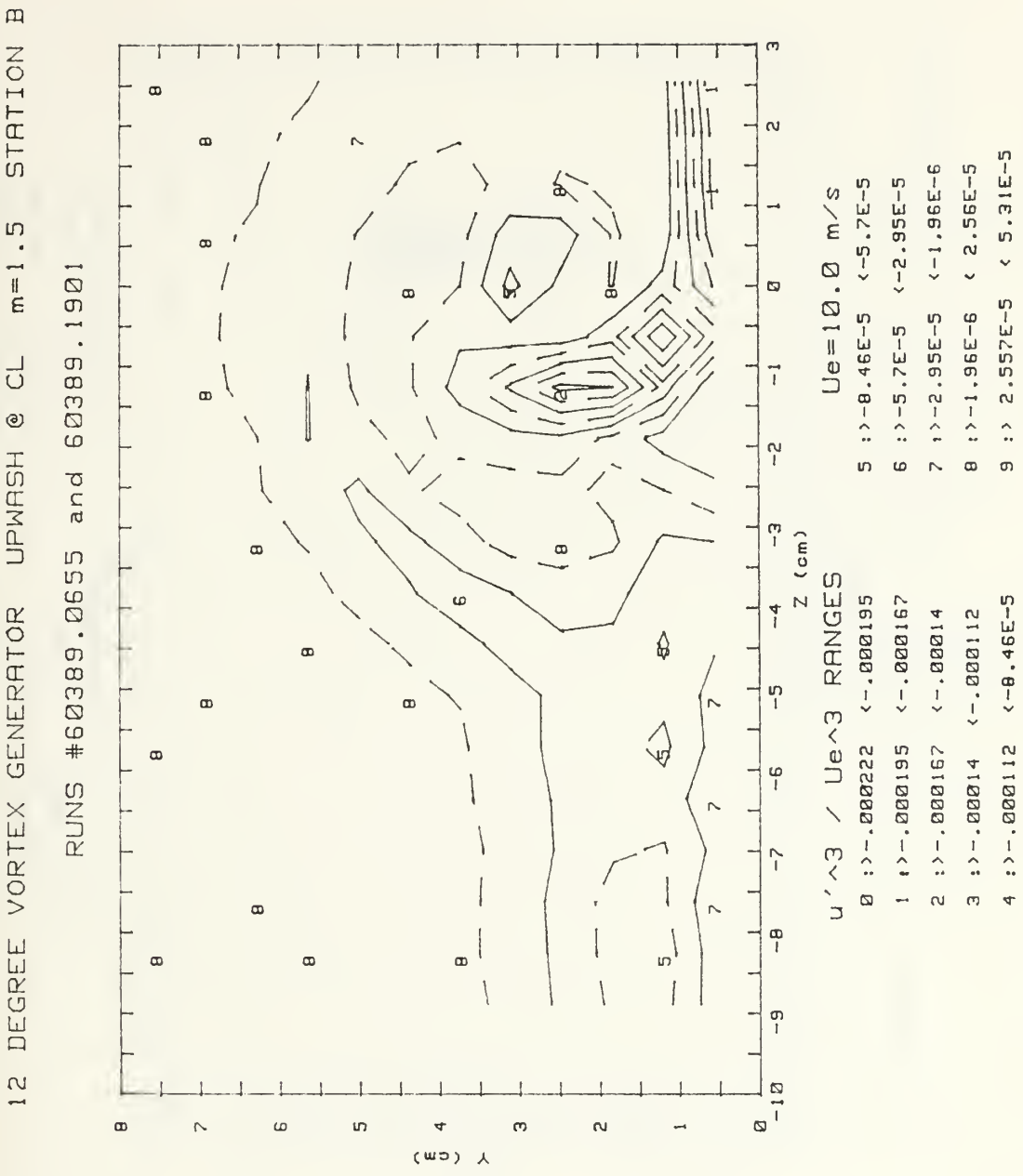

Figure 190. $\overline{u'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

Figure 191. $\overline{v'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

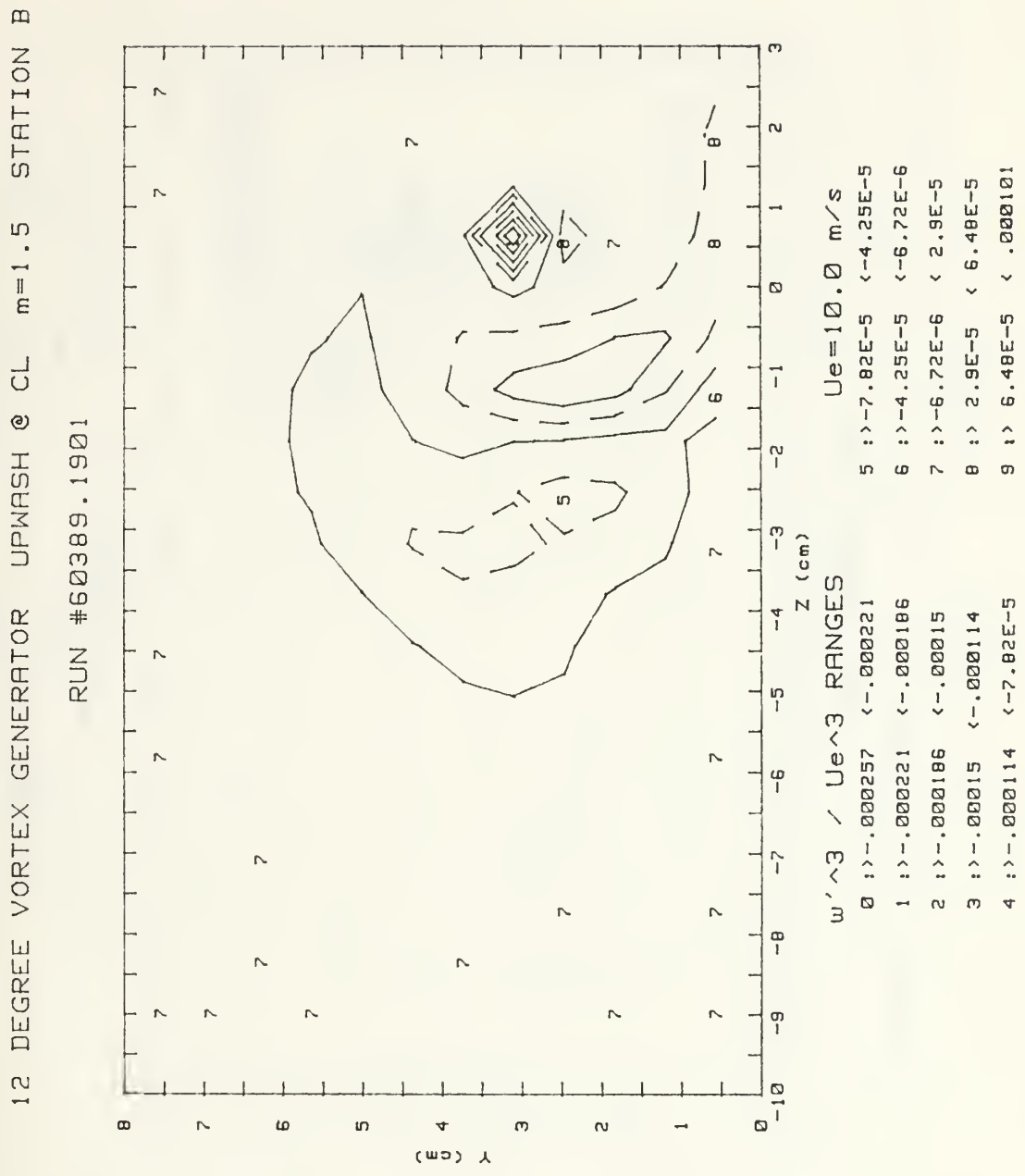

Figure 192. $\overline{w'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

Figure 193. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

Figure 194. $\overline{u'v'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

Figure 195. $\overline{u'^2w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

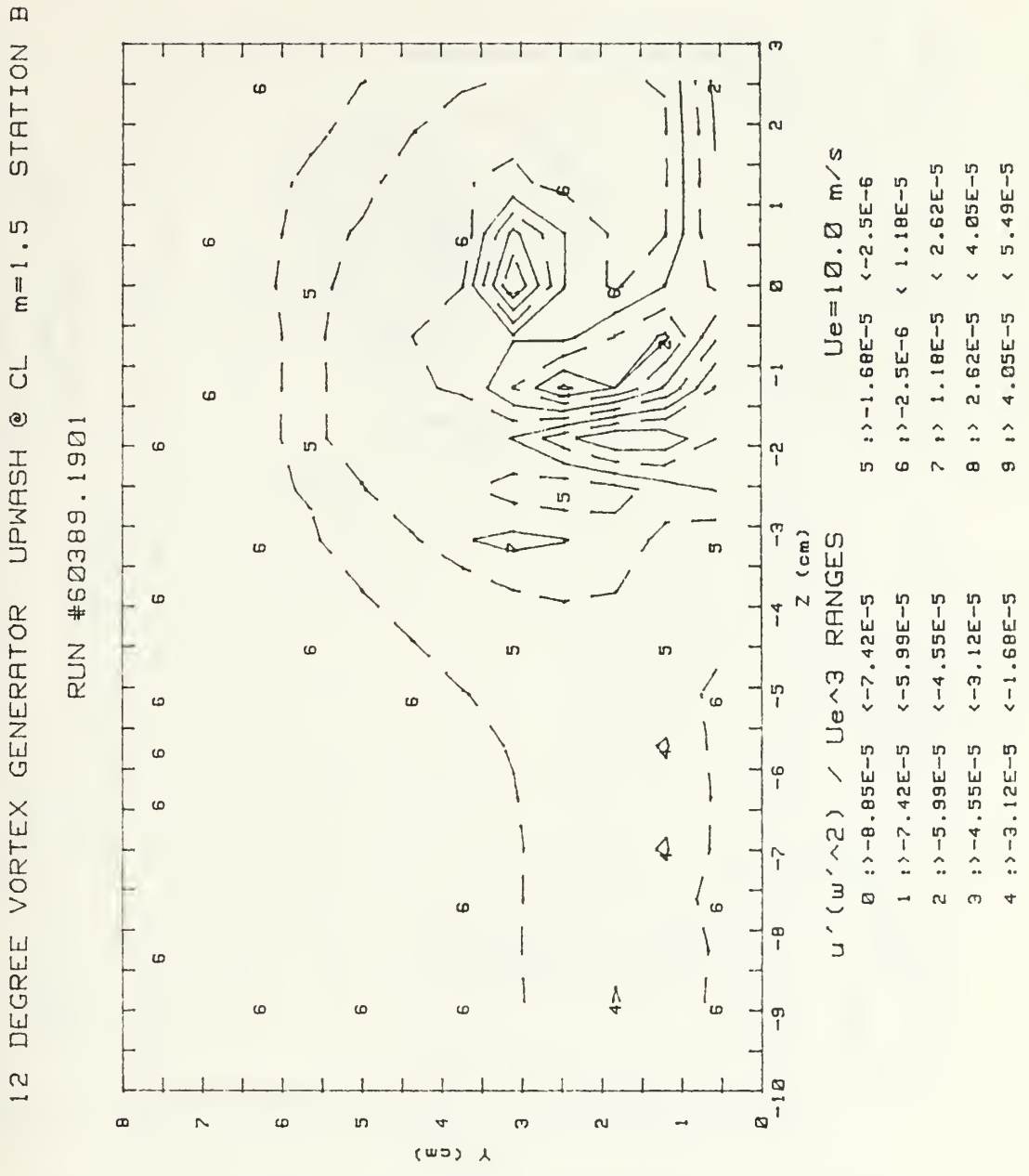

Figure 196. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

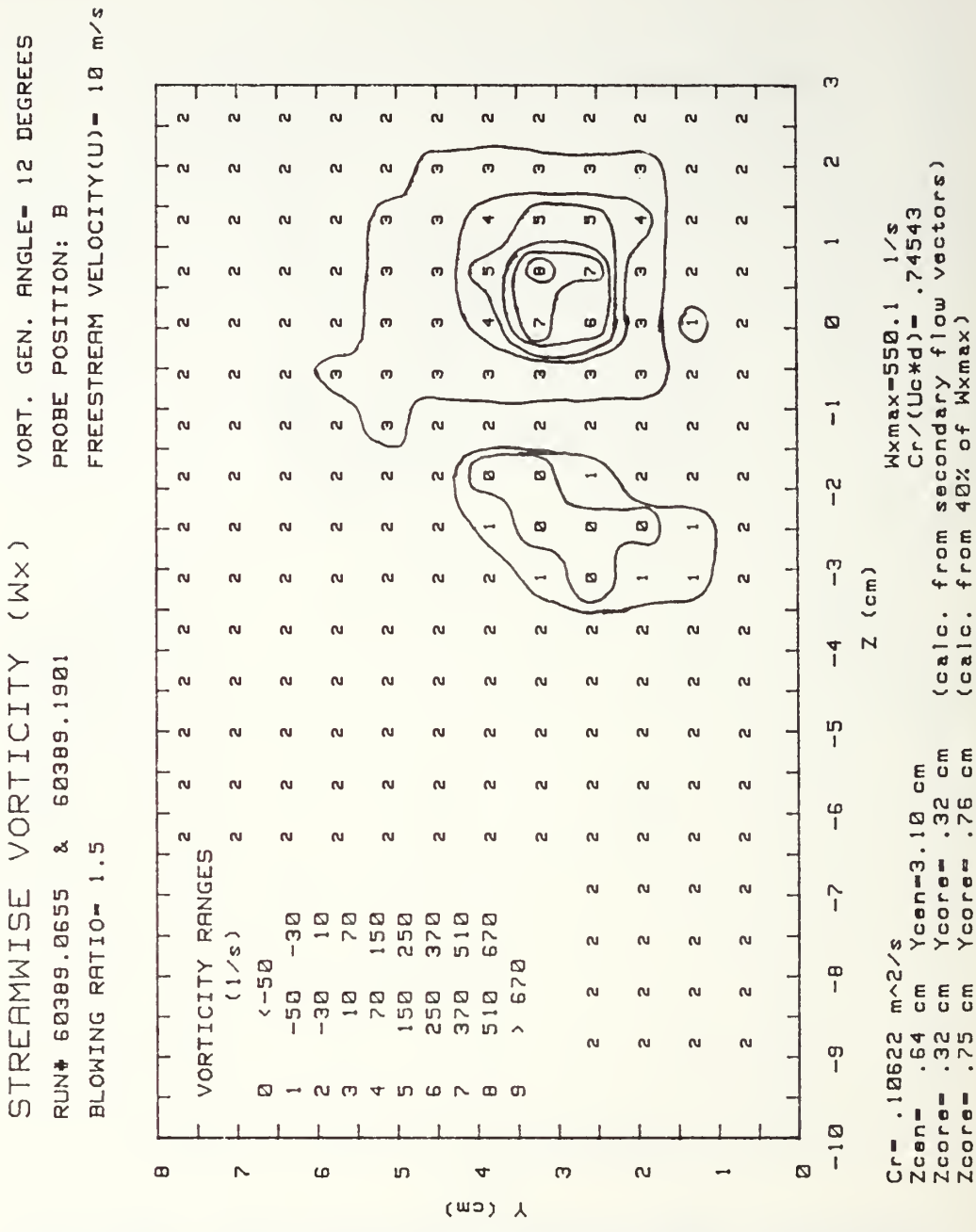

Figure 197. Streamwise Vorticity (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 1.5, Δ = 0.25)

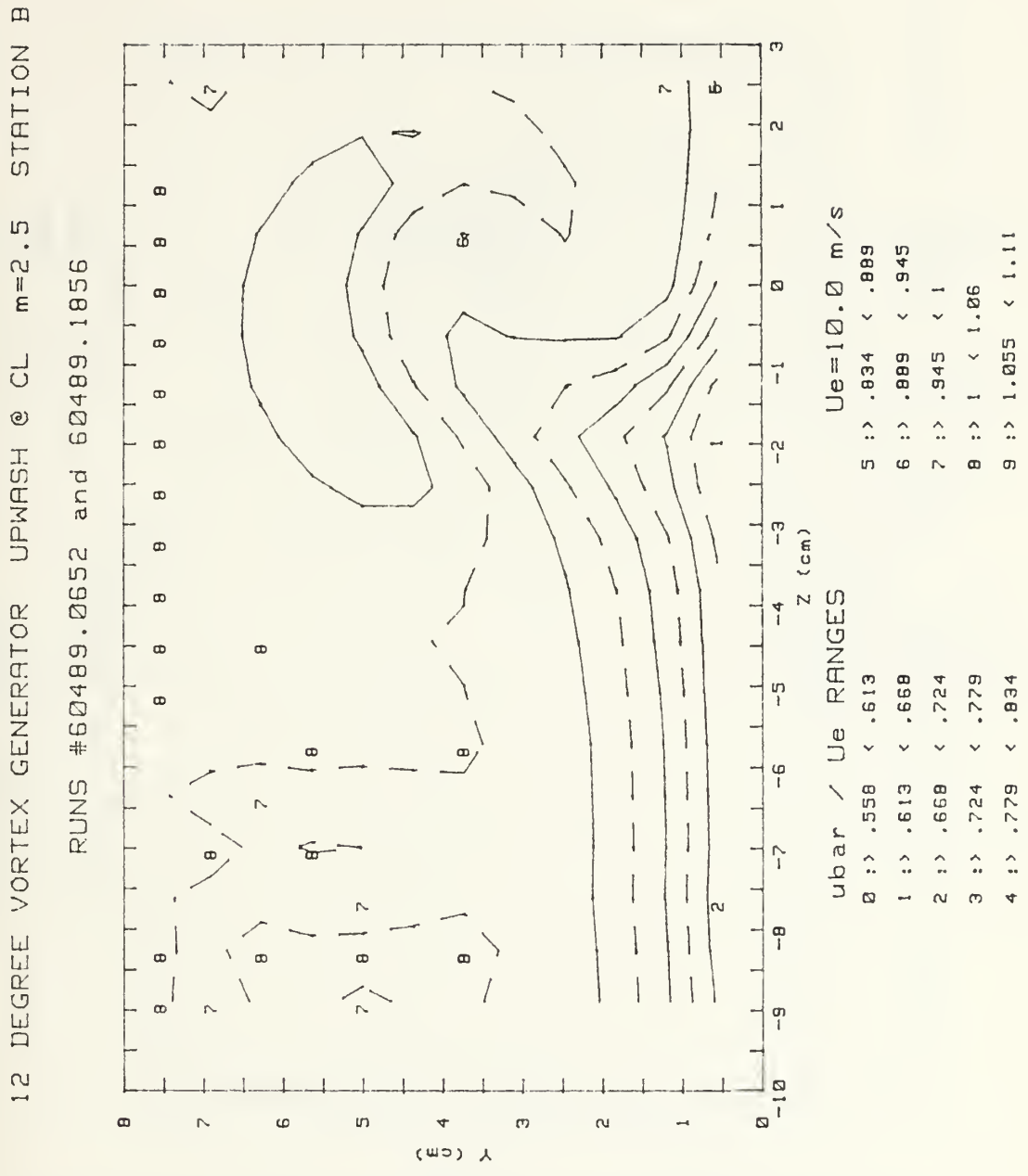

Figure 198. $\bar{u}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 199. $\overline{v}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

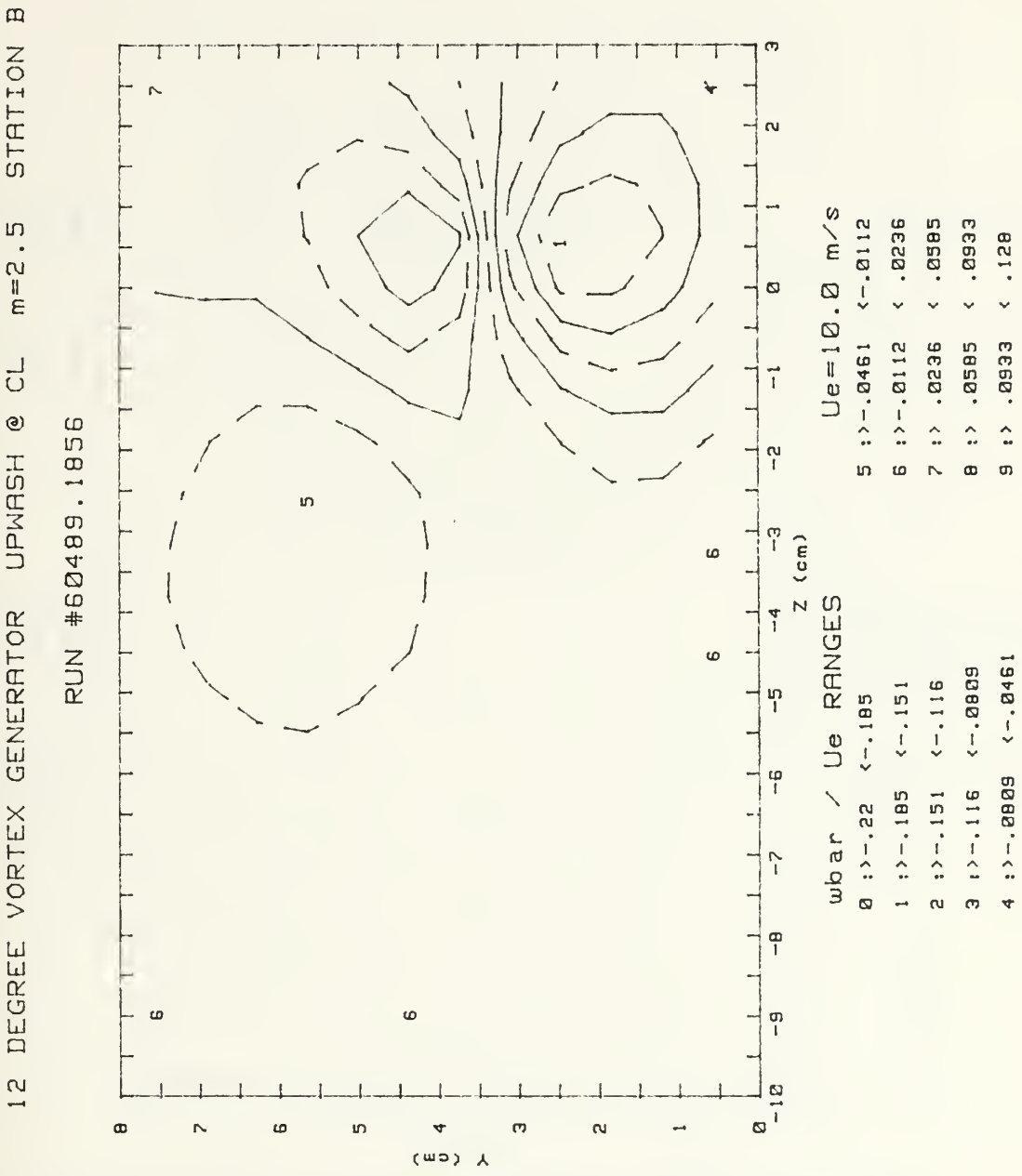

Figure 200. $\overline{w}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 201. $\overline{u'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 202. $\overline{v'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 203. $\overline{w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 204. $\overline{u'v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 205. $\overline{u'w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 206. $\overline{u'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 207. $\overline{v'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 208. $\overline{w'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 209. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 210. $\overline{u'v'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

Figure 211. $\overline{u'^2w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

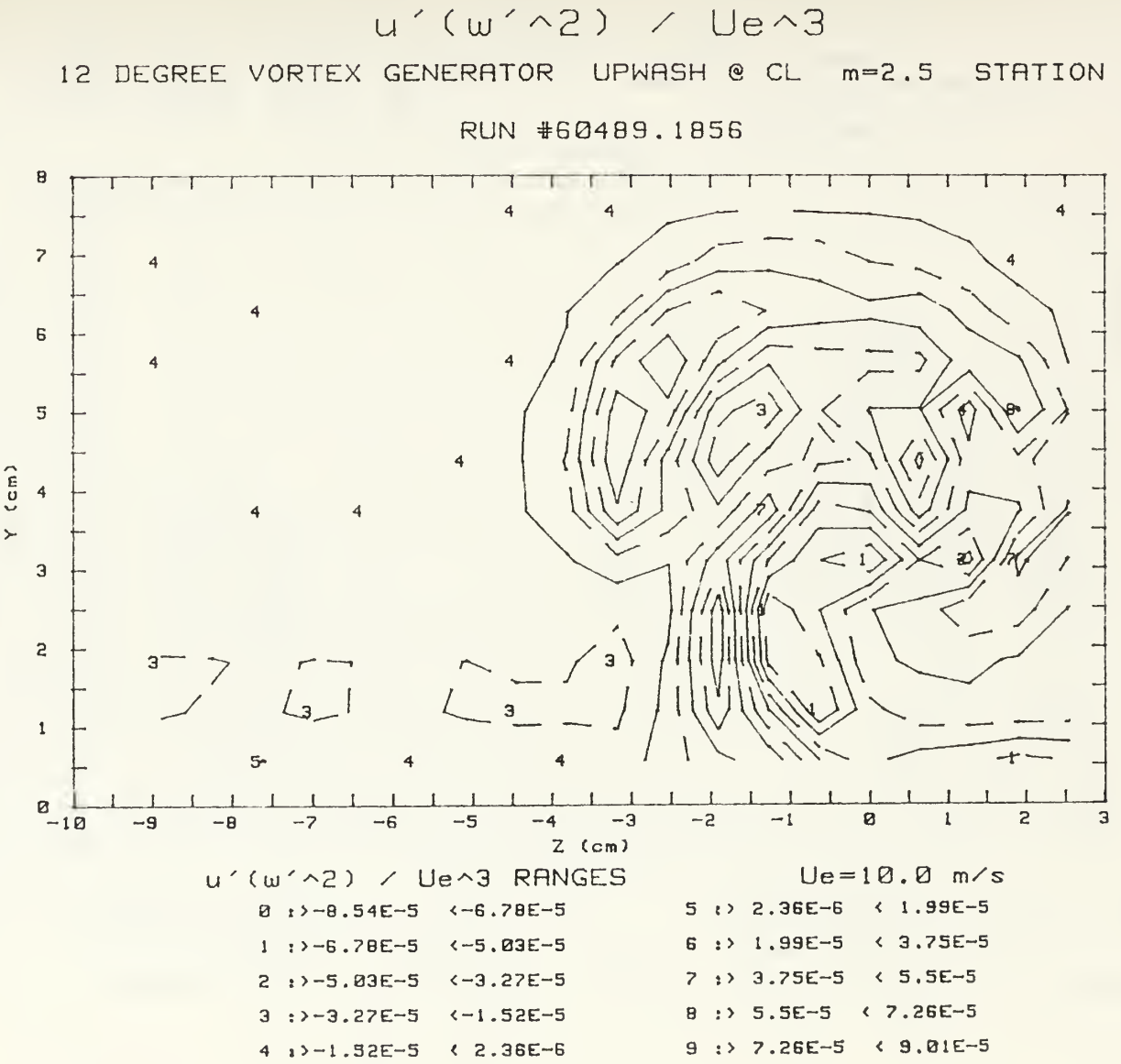

Figure 212. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

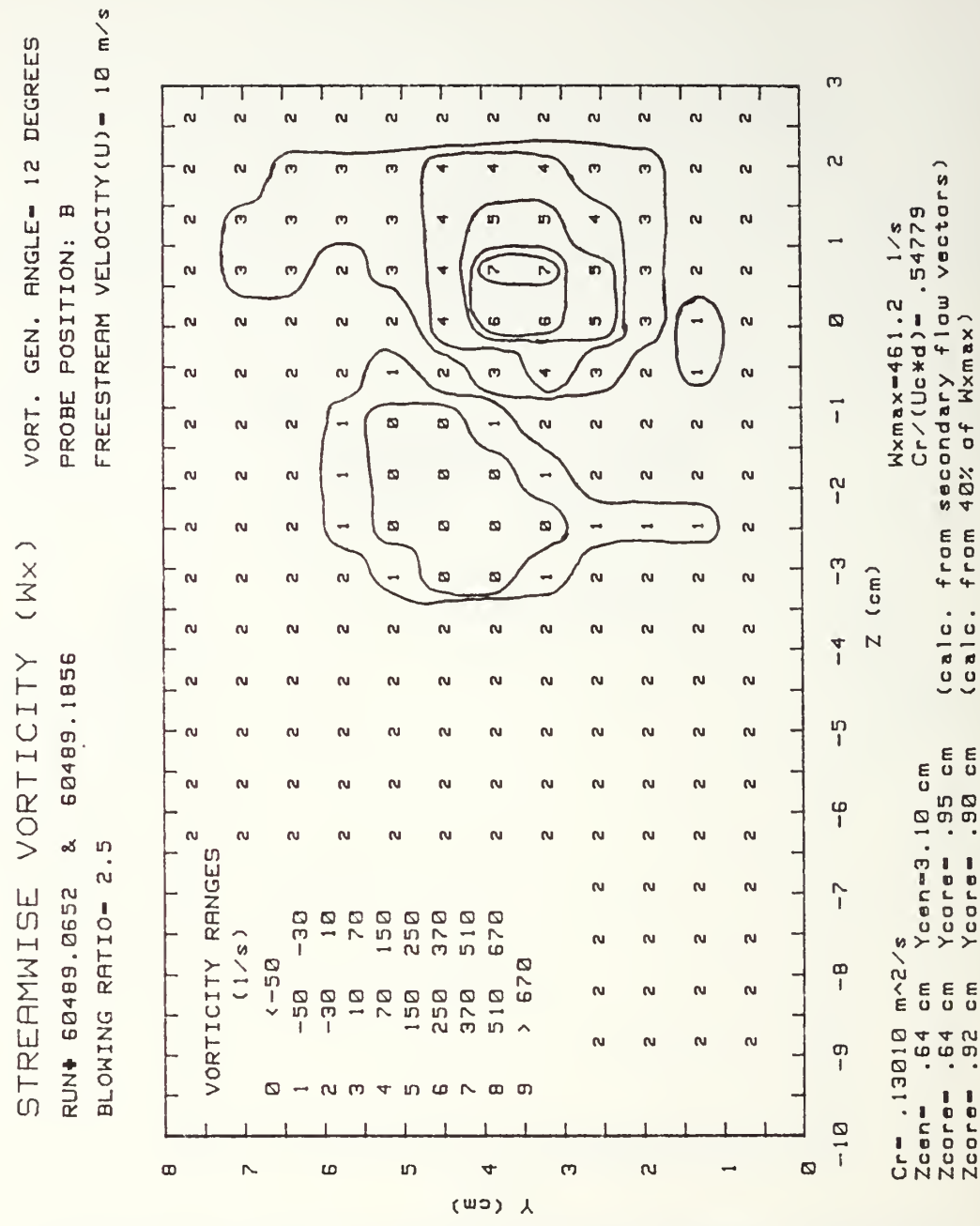

Figure 213. Streamwise Vorticity (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 2.5, Δ = 0.25)

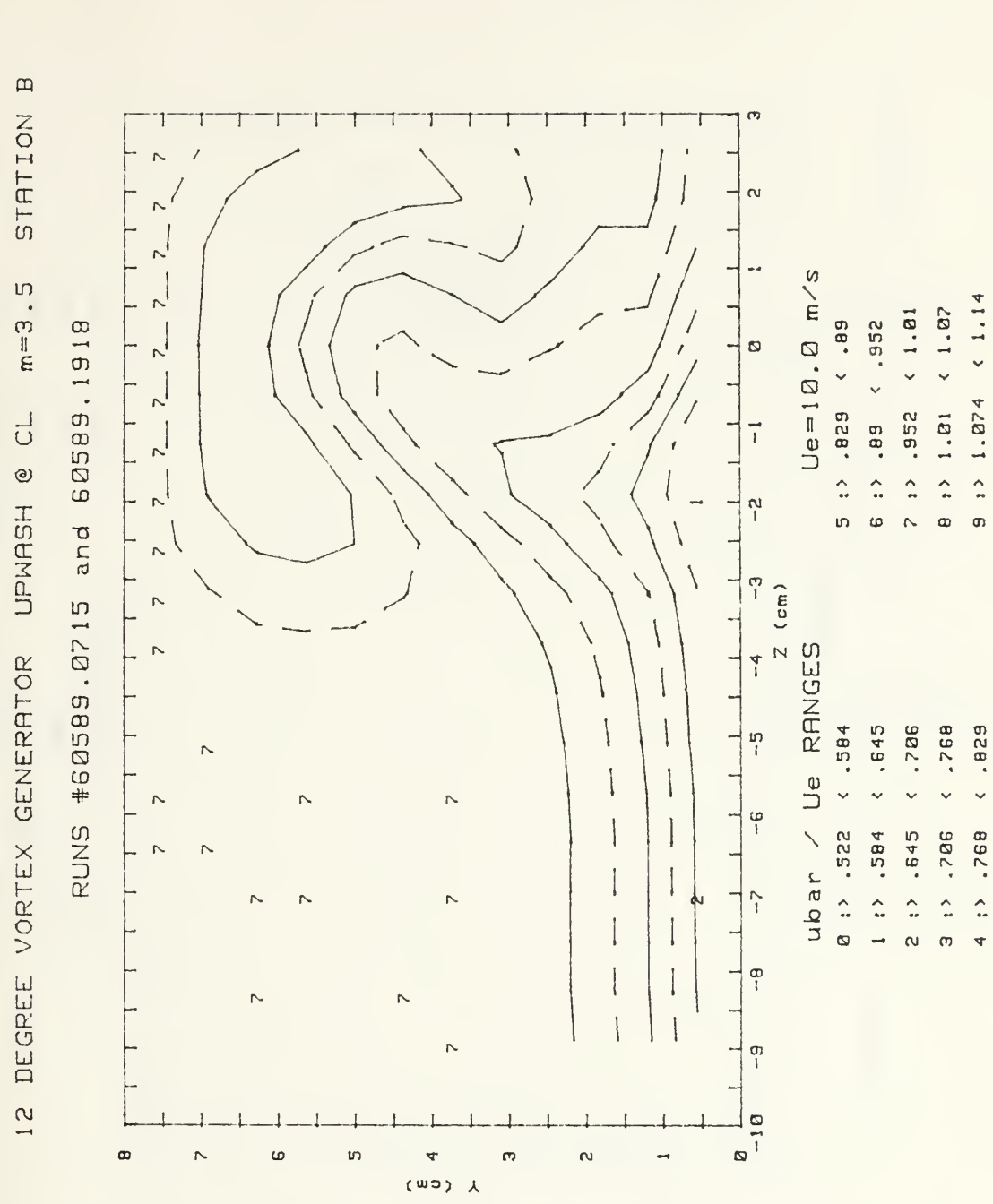

Figure 214. $\tilde{u}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

Figure 215. $\bar{v}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

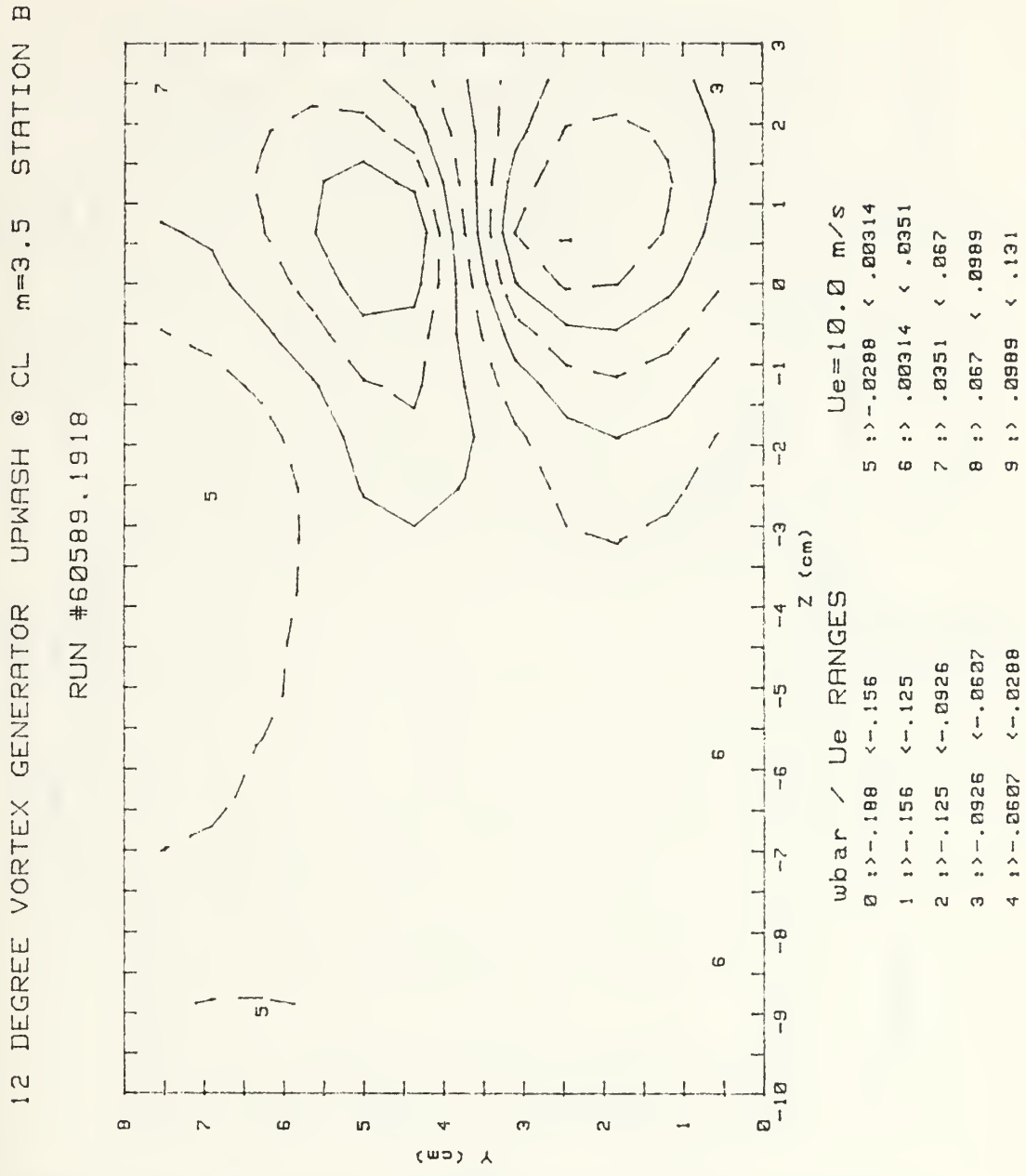

Figure 216. $\bar{w}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

Figure 217. $\overline{u'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

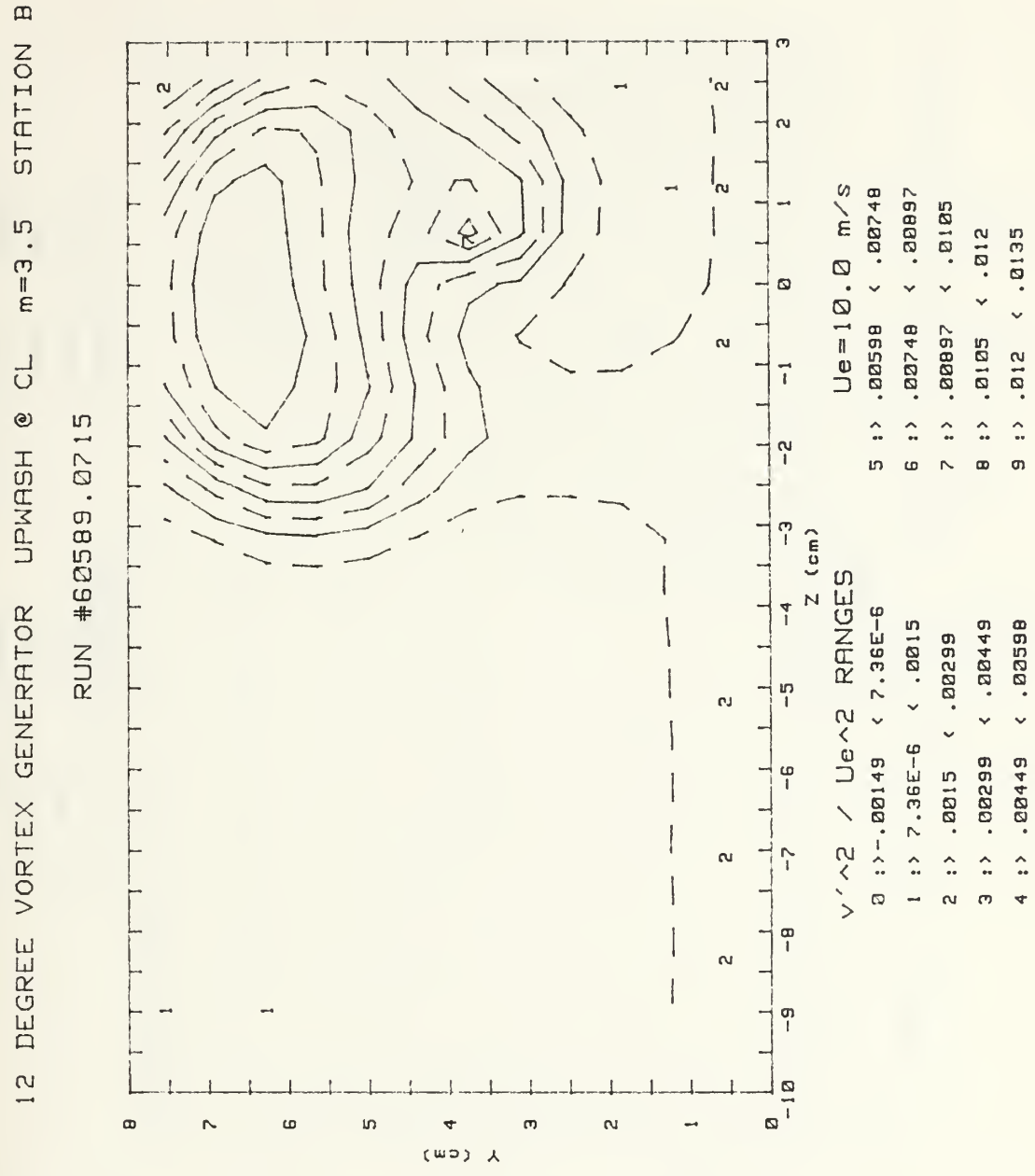

Figure 218. $\overline{v'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

Figure 219. $\overline{w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

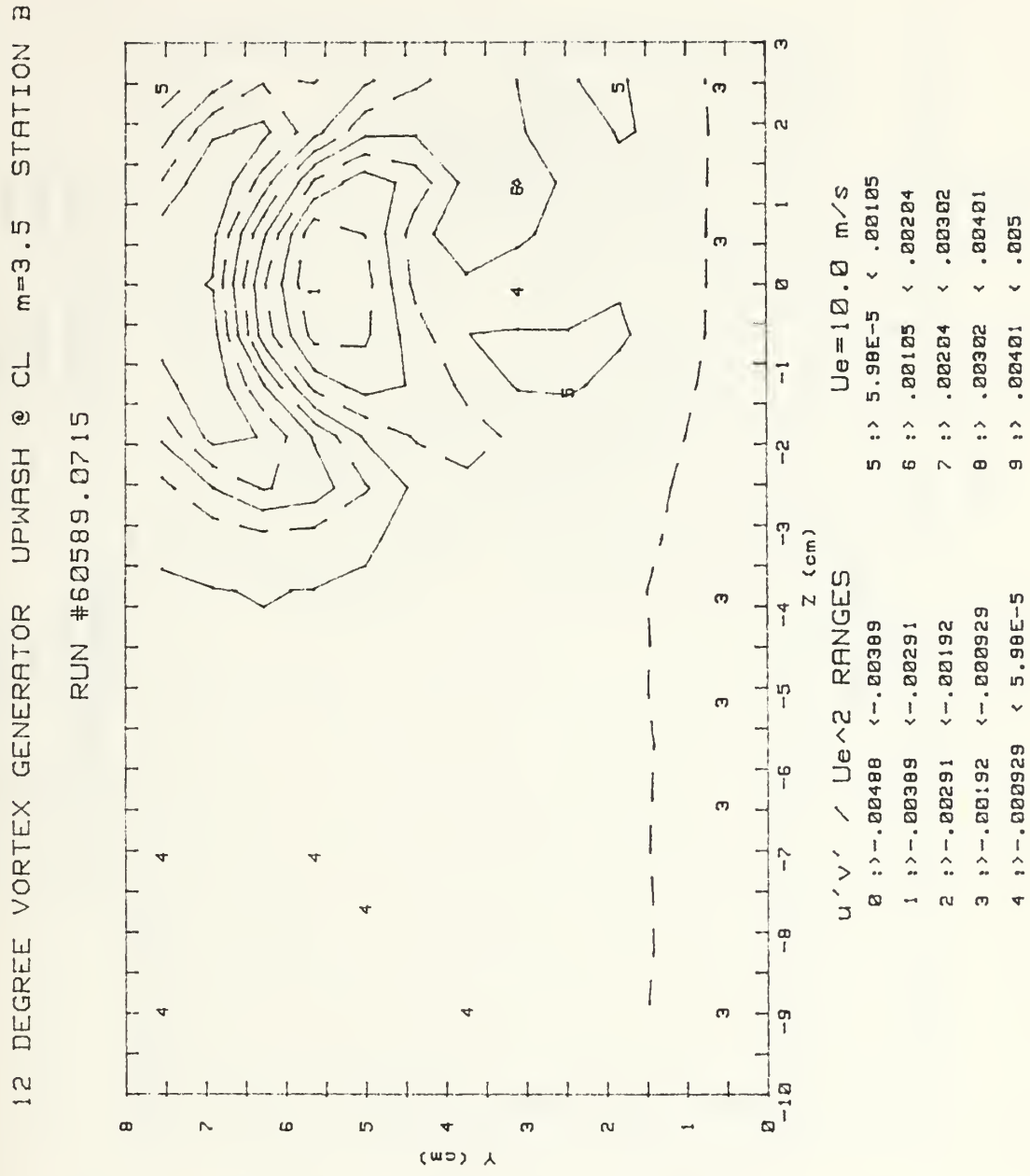

Figure 220. $\overline{u'v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

Figure 221. $\overline{u'w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

Figure 222. $\overline{u'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

Figure 223. $\overline{v'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

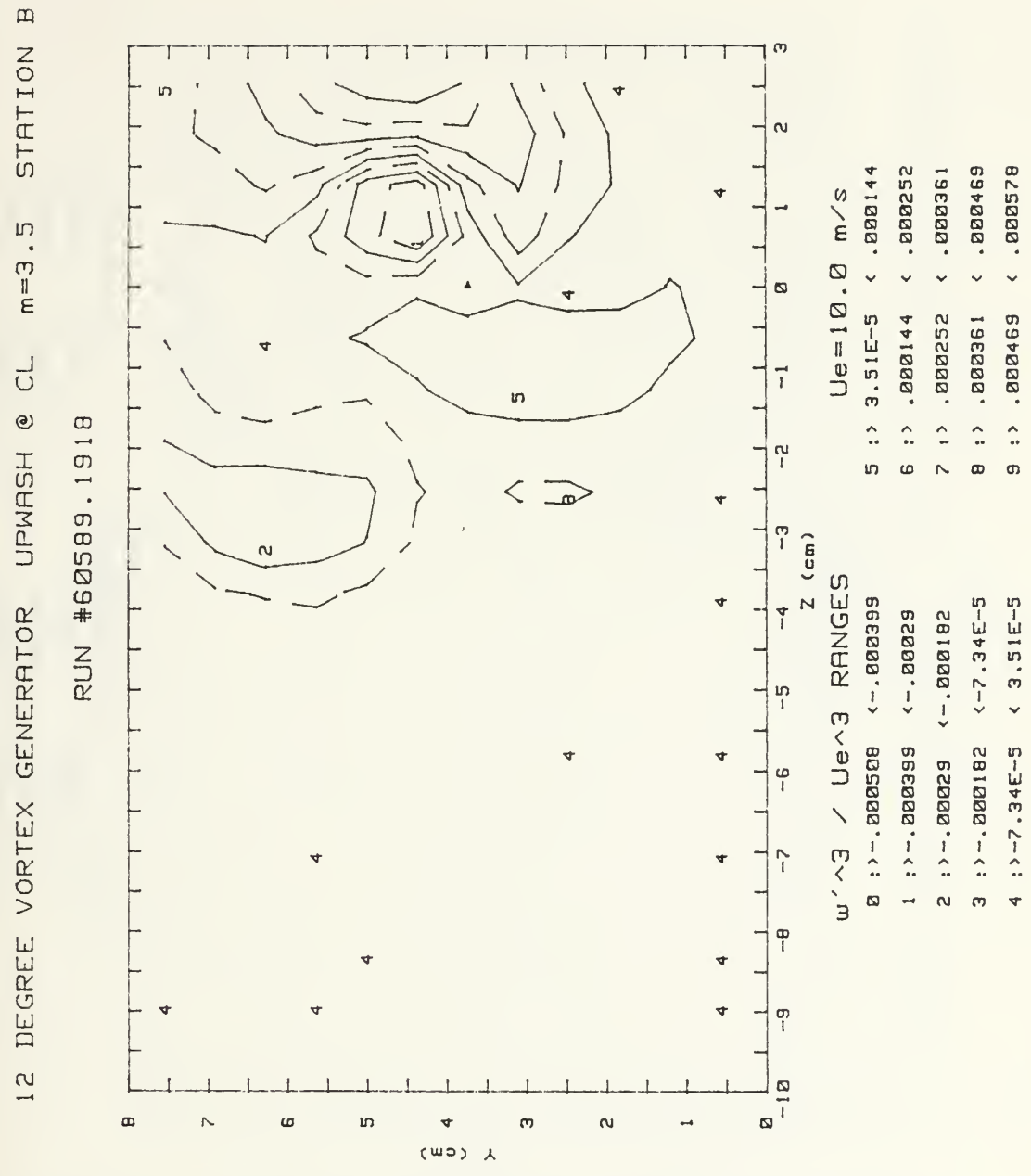

Figure 224. $\overline{w'^3}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

Figure 225. $\overline{u'^2v'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

Figure 226. $\overline{u'v'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

Firure 227. $\overline{u'^2 w'}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

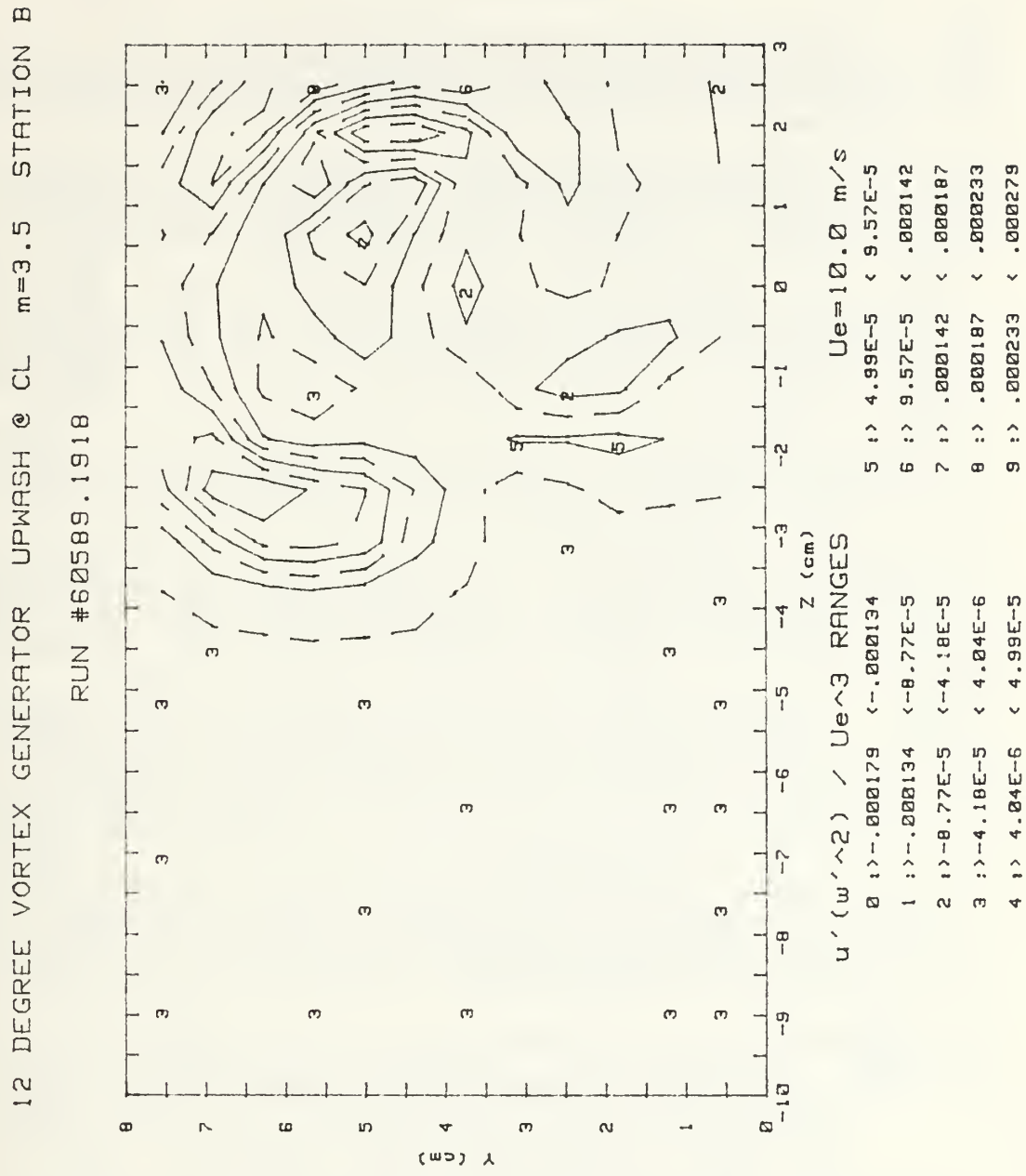

Figure 228. $\overline{u'w'^2}$ (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

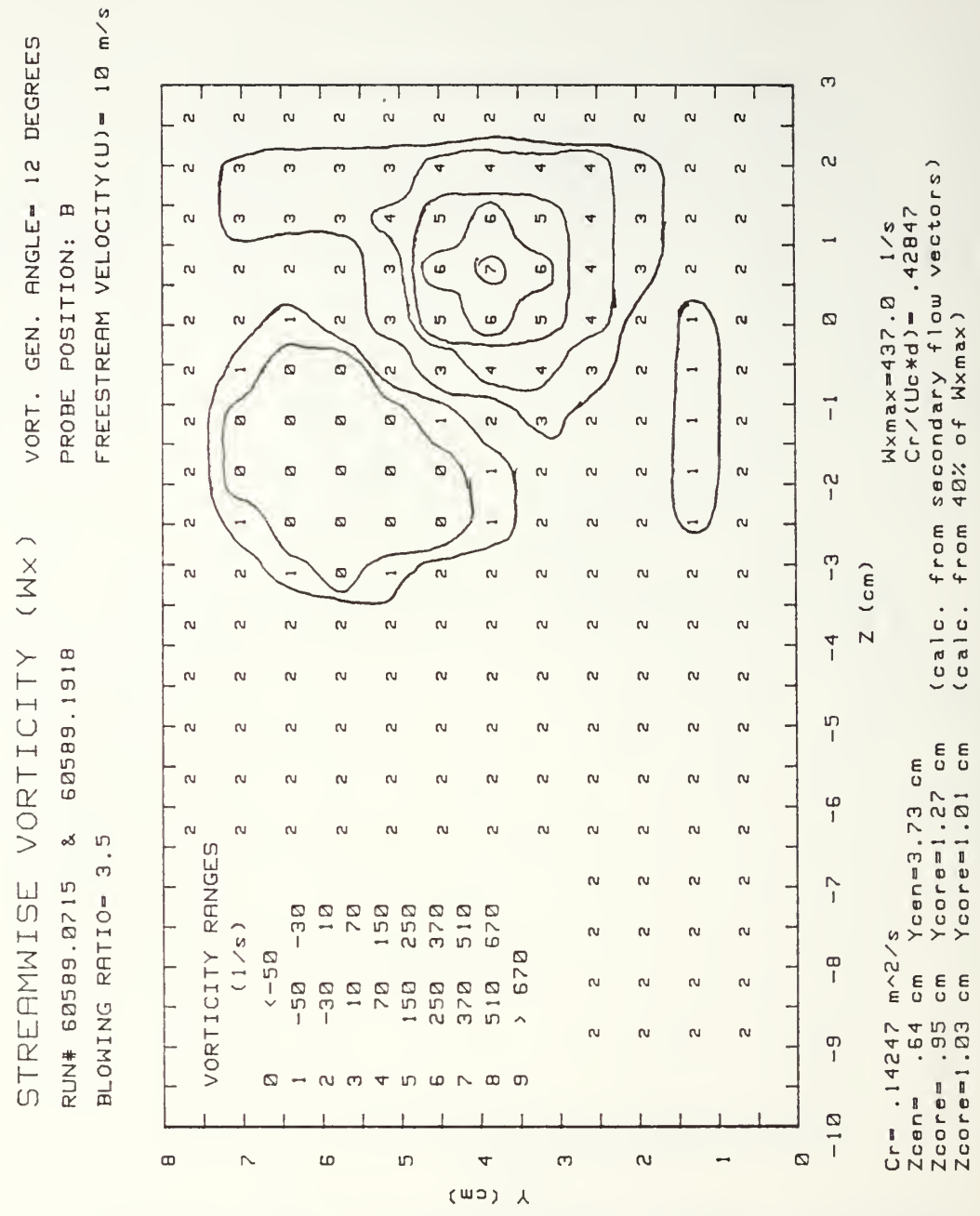

Figure 229. Streamwise Vorticity (Boundary Layer w/vortex, Upwash @ Centerline, Station B, m = 3.5, Δ = 0.25)

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